

Spring 1-1-2011

Multi-Polarized Spiral Antennas for RF Sensing

William Neill Kefauver

University of Colorado at Boulder, w.neill.kefauver@lmco.com

Follow this and additional works at: http://scholar.colorado.edu/ecen_gradetds



Part of the [Electrical and Computer Engineering Commons](#)

Recommended Citation

Kefauver, William Neill, "Multi-Polarized Spiral Antennas for RF Sensing" (2011). *Electrical, Computer & Energy Engineering Graduate Theses & Dissertations*. Paper 26.

This Dissertation is brought to you for free and open access by Electrical, Computer & Energy Engineering at CU Scholar. It has been accepted for inclusion in Electrical, Computer & Energy Engineering Graduate Theses & Dissertations by an authorized administrator of CU Scholar. For more information, please contact cuscholaradmin@colorado.edu.

MULTI-POLARIZED SPIRAL ANTENNAS FOR RF SENSING

by

W. NEILL KEFAUVER

B.S.E.E., Virginia Polytechnic and State University, 1983

M.S.E.E., Virginia Polytechnic and State University, 1984

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirement for the degree of

Doctor of Philosophy

Department of Electrical, Computer, and Energy Engineering

2011

This thesis entitled:

Multi-Polarized Spiral Antennas for RF Sensing

written by W. Neill Kefauver

has been approved for the Department of Electrical, Computer, and Energy Engineering

Dr. Dejan Filipovic

Dr. Edward Kuester

Date_____

The final copy of this thesis has been examined by the signatories, and we
Find that both the content and the form meet acceptable presentation standards
Of scholarly work in the above mentioned discipline.

Kefauver, W. Neill (Ph.D., Electrical, Computer and Energy Engineering)

Multi-Polarized Spiral Antennas for RF Sensing

Thesis directed by Assistant Professor Dejan S. Filipovic

Abstract

Spiral antennas are capable of dual polarized operation if the currents can propagate along their arms by going either out or in through the radiation region of the spiral. The wrapping sense of the spiral determines the polarization of the radiated field resulting from this current flow. There are two ways to accomplish this phenomenon over very wide bandwidths. Specifically, either have a feed point for the spiral both outside and inside the radiation region, or use of the modulated arm width (MAW) spiral antenna. The MAW spiral antenna has not been widely accepted and is seldom reported in open literature. Its geometry is however sufficiently unique from the other planar frequency independent (FI) antennas to require a complete explanation of where it fits for different applications, specifically RF sensing. The design of the MAW spiral antenna is detailed herein including geometry described by modulation period, modulation magnitude, expansion rate, total number of arms, feed point structure, termination, cavity, feeding and dielectric effects. The emphasis is on detailed understanding of its performance characteristics such as impedance, pattern control and quality. The relevance of these characteristics to the antenna being used as a sensor is explained. The specific concerns being quantified are location by angle of arrival techniques and polarization detection.

The use of a four-arm MAW spiral for angle of arrival as well as polarization sensing is demonstrated theoretically and experimentally. This combined capability has not been mentioned in any literature previously and was investigated thoroughly under this thesis to determine the limitations since as found herein no other four-arm FI planar antenna has this capability. In addition, the application of several geometries of the MAW spiral are examined as possible improvements over the original equiangular geometry including Archimedean, bi-layer, and

structures that are not self-complementary due to either the modulation ratio or the period. In particular, pattern performance improvement is demonstrated for modulation periods that do not produce self-complementary geometries while having minimal impact on impedance. Finally, an investigation into the asymmetric modes for an arbitrary number of arms was conducted to evaluate the performance limits of the highest available mode (mode with the largest phase change between arms) of a MAW spiral. Typically, this highest mode has significantly poorer performance than the other modes due to the inability of the MAW spiral to separate it from the modes that are not controlled by the beamformer.

DEDICATION

*to my parents, who taught me learning was much more interesting journey than any destination, and
especially to my brother who has taken all the roads first for me*

ACKNOWLEDGEMENTS

I am grateful to my academic advisor, Prof. Dejan S. Filipovic, for his support and guidance throughout my Ph.D. program. He provided me with opportunities for a variety of research topics, which included TM waveguide arrays, artificial dielectrics, implementing several measurement techniques, many different implementation of frequency independent antennas including modulated arm width spiral antennas, and modeling methods for numerical analysis. Particularly, I am deeply thankful for his understanding and patience of helping me balance the requirements of my job and my odyssey of self-discovery in the areas of academic research. I would also like to thank Prof. Edward Kuester, Prof. Zoya Popovic, Prof. Melinda Picket-May, and Dr. Mark Ablowitz for serving as my thesis committee members.

This work has been partly supported by ONR (Office of Naval Research) of which the program manager is Dr. Peter Craig for our grant “Antennas from VHF to THz”. I would also like to thank Lockheed Martin for funding my education and Steve Rossi and Thomas Cencich for helping me prepare my research paper and provide additional resources including antenna range time.

I would also like to thank my colleagues and friends; Prof. Filipovic's group: Ki Chul Kim, Joseph Mruk, Matthew Radway, Nathan Sutton, Mohamed Elmansouri, Rohit Sammeta; Prof. Filipovic's alumni: Dr. Yongjae Lee, Dr. Kenneth Vanhille, Nathan Stutzke, Dr. Michael Buck, Dr. Milan Lukic, Dr. Yuya Saito, Dr. James McDonald, for their help and support.

I also am extremely thankful for the support of my long suffering girlfriend, Laura Berens who has patiently endured my obsession with science.

CONTENTS

CHAPTER

1.0	INTRODUCTION	1
1.1	Motivation and Applications.....	1
1.2	Frequency Independent Antennas	4
1.3	MAW Spiral Antennas.....	8
1.4	Dispersion in Planar FI Antennas	9
1.5	Thesis Organization	9
2.0	DUAL-POLARIZED MAW SPIRAL ANTENNAS	11
2.1	Geometry of Frequency Independent Antennas	11
2.2	Theory of Operation.....	14
2.2.1	Bandstop Design	16
2.2.2	Dispersion in FI Antennas	21
2.3	Modeling.....	26
2.3.1	Finite Element Modeling	28
2.3.2	Dielectric.....	29
2.3.3	Cavity.....	29
2.3.4	Archimedean Geometries.....	30
2.3.5	Arm width Ratios that are not Self Complementary.....	36
2.3.6	Bi-Layer Geometries.....	39
2.4	Design and Parametric Study.....	44
2.4.1	Spiral Antenna Contribution to the MAW Spiral	44
2.5	Performance Measures.....	46

2.5.1	Polarization	46
2.5.2	Beamformer Modal Purity	47
2.5.3	Pattern Purity	48
2.5.4	Termination.....	48
2.5.5	Ripple from Modulation	50
2.5.5	Current Behavior.....	52
2.6	Antenna Performance from Parametric Study	55
2.7	Measurements	59
2.8	Summary	63
3.0	AOA IN FOUR-ARM SPIRALS	65
3.1	MAW Spiral Capability	66
3.2	Place for MAW Spiral in the FI Antenna Family	73
3.3	Mode 2 Cross-Polarization	77
3.4	Beamformer Requirements for Four-Arm Geometry	77
3.4.1	Orthogonal Behavior of Modes	79
3.4.2	Parallelism of Modes	82
3.5	Phase Center Variation	87
3.6	Impedance	88
3.7	Measurement Validation.....	89
3.8	Summary	93
4.0	NON-SELF-COMPLEMENTARY DESIGN INVESTIGATION	94
4.1	MAW Spirals that are not Self-Complementary.....	94
4.2	Radiation Patterns	97
4.3	Full Model Geometry with Cavity and Dielectric	102

V.	MULTI-ARM CAPABILITIES.....	108
5.1	Theory	109
5.1.1	Beamformer	110
5.1.2	Patterns of Multi-Arm MAW Spirals	111
5.1.3	Simulated AoA.....	115
5.2	Archimedean Comparison	117
5.3	Phase Center Variation	120
VI.	CONCLUSIONS.....	122
6.1	Summary of Work and Contribution	122
6.2	Future Work	125
	BIBLIOGRAPHY	127

TABLES

Table

0.1.	Average gains (dBic) of self-complementary equiangular and Archimedean MAW spirals with different modulation ratios.....	35
0.2.	Average cross-polarization (dB) for self-complementary equiangular and Archimedean MAW spirals with different modulation ratios	35
0.3.	Average WoW (dB) at $\theta = 30^\circ$ for equiangular and Archimedean spirals with self-complementary geometry with different modulation ratios	36
0.4.	Comparison of average broadside gains (dBic) between the self- and non-self-complementary Archimedean MAW spirals	37
0.5.	Comparison of average cross-polarization (dB) between self- and non-self-complementary Archimedean MAW spirals, elevation angle is $\theta = 30^\circ$	39
0.6.	Computed average broadside gain (dBic) for different modulation and expansion factors (no ohmic losses included). G_f is gain in forward operation and G_r is gain in reverse operation.....	56
0.7.	Computed average relative cross-polarization at $\theta = 30^\circ$. X_f is cross-polarization in forward operation and X_r is cross-polarization in reverse operation..	56
0.8.	Computed average relative cross-polarization at $\theta = 60^\circ$. X_f is cross-polarization in forward operation and X_r is cross-polarization in reverse operation..	57

FIGURES

Figure

1.1.	AOA sensing coordinate system	3
1.2.	Response of the channel ratio for a four-arm spiral at $10f_0$	3
2.1.	Studied four-arm FI geometries	12
2.2.	Illustration of a Bandstop for a four-arm MAW spiral antenna.....	15
2.3.	Impedance property of coplanar microstrip versus gapwidth	17
2.4.	Reflection and transmission of bandstop section modeled at 2λ circumference. T is transmission through the bandstop, Γ is reflection from the bandstop, m_n is the modulation of the spiral arm	19
2.5.	Delay of the modes of the three different FI antennas	22
2.6.	Overlaying the sinuous and spiral geometry to correlate expansion factors.....	22
2.7.	Group dispersion of planar FI antennas	23
2.8.	Currents for single arm and three modes of operation, $4f_0$	24
2.9.	Bandstop current detail on the MAW spiral	25
2.10.	Input impedance of a MAW spiral with modulations of 89% (8:1) and two layer of 150%	26
2.11.	Effects of mesh asymmetry on broadside gain for MAW spiral with the growth of 2 and modulation of 4 that is fed with wire probes, ‘nominal’ refers to the automatic mesh by FEKO, ‘symmetric’ refers to the enforced mesh symmetry.....	27
2.12.	A layout of an Archimedean self-complementary four-arm MAW spiral with modulation ratio of 4.	31
2.13.	Four-arm Archimedean (a) and equiangular (b) spirals.....	33
2.14.	Example of non-self-complementary MAW Archimedean spiral, combining the low impedance sections from 8:1 MAW spiral and high impedance sections from 2:1 MAW spiral (of the self-complementary type).....	36
2.15.	Input resistances of Archimedean self-complementary	38
2.16.	Input resistances of Archimedean non-self-complementary MAW spirals with the low impedance section metal to slot width ratio of 8:1.	38
2.17.	Exaggerated bi-layer equiangular spiral with 12:1 modulation and large separation to show two layers.....	40
2.18.	Impedance for different spacings between the layers	40

2.19.	Pattern cross-polarization (x-pol) for antenna with 50% arm overlap and 12:1 modulation ratio at: broadside with different spacings between layers.....	41
2.20.	Pattern cross-polarization (x-pol) for antenna with 50% arm overlap and 12:1 modulation ratio at $\theta=30^\circ$	41
2.21.	Cross-polarized gain for the reverse mode of operation for 8:1 and 12:1 modulation ratios with a single and dual layer MAW spirals (a), and forward and reverse cross-polarized gains for the dual layer MAW spiral.....	42
2.22.	Cross-polarized gain for the dual layer MAW spiral, separation of $0.0027\lambda_0$	43
2.23.	Pattern comparison of planar versus dual (bi)-layer Archimedean MAW with $0.0027\lambda_0$ spacing and 50% overlap at $f=6f_0$	43
2.24.	Layout of planar MAW spirals with expansion and modulation of: (a) 3 and 2, (b) 3 and 8, (c) 1.25 and 2, (d) 1.25 and 8.	44
2.25.	Simulated reverse operation broadside gain near cutoff for different termination lengths in the final bandstop with either low or high Z_0	49
2.26.	MAW Spiral termination geometry with the different cut locations for Figure 2.25	49
2.27.	Simulated broadside gain for different expansion factors. MAW spiral is terminated by the low-impedance termination (45° low Z_0 in Figure 2.25), and its modulation is set at 8.	51
2.28.	Simulated results for antenna input resistance (top) and reactance (bottom) variation over frequency. Modulation of 8 has a quarter turn matching section, modulations of 2 and 4 have full turn transmission line launches.	52
2.29.	Coupling for arms before (a) and after (b) feed point term is removed	54
2.30.	Performance of a single arm of a four-arm MAW spiral compared to four-arm performance.	54
2.31.	Arm beam location, (a) off broadside point, (b) frequency tracking rotation.....	55
2.32.	Computed forward ($M=+1$) and reverse ($M=-1$) average WoW at 30° for different MAW spiral expansion factors and modulation ratios.....	58
2.33.	Computed forward ($M=+1$) and reverse ($M=-1$) average WoW at 60° for different MAW spiral expansion factors and modulation ratios.....	58
2.34.	Photograph of a fabricated MAW spiral with expansion of 3, modulation of 4 and non-complementary center region.....	59
2.35.	Measured gain for the forward ($M=+1$) and reverse ($M=-1$) modes by the ideal beamformer methods at $\theta=30^\circ$, $\phi=0^\circ$	61
2.36.	Dielectric loading effects on WoW at 60° using measurements and simulations denoted in superscript as “m” and “c”, respectively. Subscripts denote: “n” for all n arms excited, “1” for one arm excited, “fs” for free-standing MAW computed using free-space Greens function, and “6002” for Rogers dielectric 6002 computed using MLGF.....	61
2.37.	Forward ($M=+1$) and reverse ($M=-1$) WoW at $\theta= 30^\circ$ obtained using modeling (MLGF), and single arm measurements.....	62

2.38.	Forward ($M=+1$) and reverse ($M=-1$) WoW at $\theta=60^\circ$ obtained using modeling (MLGF), and single arm measurements.....	62
2.39.	Cross-polarization for reverse mode at $\theta=30^\circ$ and 60° obtained using modeling (MLGF) and single arm measurements.....	63
2.40.	Computed and measured S-parameters using HFSS [44].....	64
3.1.	Gain of antennas in (a) RCP sum mode at 30° , (b) x-pol of sum mode operation.....	71
3.2.	Off axis 30° (a) co-pol of difference mode, (b) x-pol of difference mode.....	72
3.3.	Off axis 30° (a) co-pol of reverse sum mode, (b) x-pol reverse sum mode.....	73
3.4.	Patterns at $10f_0$ of a four-arm MAW spiral.....	75
3.5.	Patterns at $10f_0$ of a four-arm sinuous.....	75
3.6.	Patterns at $10f_0$ of a four-arm spiral.....	76
3.7.	Comparison of mode $= -1$ (a) and 2 (b) cross- polarization for three MAW spiral geometries at $\theta = 30^\circ$	78
3.8.	Mode 2 at $14f_0$ (a) phase progression and, (b) gain of each polarization.....	79
3.9.	Butler matrix beamformer.....	79
3.10.	WoW _{rcp} of mode 2 at $\theta = 30^\circ$ for RCP (co-pol).....	81
3.11.	WoW _{θ} for θ linear polarization in mode 2 at $\theta = 30^\circ$	81
3.12.	Measurement results for beamformer constructed from commercial hybrids in Figure 3.13... 82	
3.13.	Picture of the (a) assembled beamformer from COTS hybrids and (b) AoA self-complementary MAW spiral with 4:1 modulation and expansion factor of 1.5.....	83
3.14.	Power reflected into antenna from beamformer	83
3.15.	Raw AoA accuracy with delay line.....	84
3.16.	AoA performance emitter for both linear polarizations at $14f_0$	86
3.17.	Frequency averaged AoA performance emitter linear polarized	86
3.18.	Phase center variation of a MAW antenna at 60° , expansion factor 1.5, and modulation ratio 87	
3.19.	Impedance of MAW spiral (sum and difference) with modulation of 4 and expansion factor 1.5	88
3.20.	Measured average mode gains of a four-arm MAW spiral with expansion of 1.5 and modulation ratio of 4 at 30° using beamformer	89
3.21.	Measured average results of a four-arm MAW spiral with expansion of 2 and modulation of 4 at $\theta=30^\circ$, beamformer losses compensated.....	90
3.22.	Measured average mode gains using single arm responses and summing through a mathematical beamformer	91

3.23.	Average measured mode gains with one arm rotated to replace all other arms.....	92
3.24.	Comparison of average response to the theoretical response of the MAW spiral with an expansion factor of 1.5 and a modulation of 4 in a 2.5 cm cavity with 3 layer commercial absorber and a 0.5 mm substrate.....	92
4.1.	Layout of planar MAW spirals with expansion and modulation of: 1.5 and 4, τ equals (a), 3 (b), 3.5 (c), 4 and (d) 5	96
4.2.	$M = \pm 1$ impedance of planar four-arm MAW spirals with (a) in the top left hand corner, $\tau = 3$, (b) upper right hand corner, $\tau = 3.5$, (c) lower left hand corner, $\tau = 4$, and (d) lower right hand corner, $\tau = 5$	98
4.3.	$M = 2$ impedance of planar four-arm MAW spirals with (a) in the top left hand corner, $\tau = 3$, (b) upper right hand corner, $\tau = 3.5$, (c) lower left hand corner, $\tau = 4$, and (d) lower right hand corner, $\tau = 5$	98
4.4.	Pattern at $\theta = 30^\circ$ of planar four-arm MAW spirals with $\tau = 3$. plot designation is mode 1 (a), mode 2 (b), mode -1 (c), free space	99
4.5.	Pattern at $\theta = 30^\circ$ of planar four-arm MAW spirals with $\tau = 3.5$. Plot designation is mode 1 (a), mode 2 (b), mode -1 (c), free space	100
4.6.	Pattern at $\theta = 30^\circ$ of planar four-arm MAW spirals with $\tau = 4$. Plot designation is mode 1 (a), mode 2 (b), mode -1 (c), free space	100
4.7.	Pattern at $\theta = 30^\circ$ of planar four-arm MAW spirals with $\tau = 5$. Plot designation is mode 1 (a), mode 2 (b), mode -1 (c), free space	101
4.8.	Modal delay between mode 2 and -1 of planar four-arm MAW spirals with various τ	102
4.9.	Average pattern at $\theta = 30^\circ$ of planar four-arm MAW spirals with $\tau = 3$. Plot designation is mode 1 (a), mode 2 (b), mode -1 (c), left to right.	103
4.10.	Average pattern at $\theta = 30^\circ$ of planar four-arm MAW spirals with $\tau = 3.5$. Plot designation is mode 1 (a), mode 2 (b), mode -1 (c), left to right.	103
4.11.	Average pattern at $\theta = 30^\circ$ of planar four-arm MAW spiral with $\tau = 4$. Plot designation is mode 1 (a), mode 2 (b), mode -1 (c), left to right.	104
4.12.	Average pattern at $\theta = 30^\circ$ of planar four-arm MAW spirals with $\tau = 5$. Plot designation is mode 1 (a), mode 2 (b), mode -1 (c), left to right	104
4.13.	Cavity performance (co-polarization), (a) mode 1, (b) mode 2, (c) mode -1.....	105
4.14.	Cavity performance (cross-polarization), (a) mode 1, (b) mode 2, (c) mode -1	105
4.15.	Effective error for uncompensated AOA of antenna from how orthogonal the polarization is between sum and difference mode (0 being the desired value)	107
0.1.	Various arm count geometries	109
0.2.	Mismatch of single arm for various arm counts	111
0.3.	Efficiency between beamformer and pattern mode for a three-arm MAW spiral	112

0.4.	Efficiency between beamformer and pattern mode for a five-arm MAW spiral	113
0.5.	Efficiency between beamformer and pattern mode for a seven-arm MAW spiral	113
0.6.	Efficiency between beamformer and pattern mode for a four-arm MAW spiral.....	114
0.7.	Efficiency between beamformer and pattern mode for a six-arm MAW spiral.....	114
0.8.	Efficiency between beamformer and pattern mode for a eight-arm MAW spiral	115
0.9.	Four-arm self-complementary MAW spiral pattern, mode 2/mode 1 (a) RCP, (b) LCP.....	115
0.10.	Five-arm self-complementary MAW spiral pattern, mode 2/mode 1 (a) RCP, (b) LCP	116
0.11.	Four-arm compared to five-arm self-complementary MAW spiral AoA statistics, mode 2/mode 1, (a) shows the spread over frequency at $\theta = 30^\circ$ for the error vector, (b) shows the average error over all frequencies and ϕ (linear weighting) by θ	117
0.12.	Broadside gains for 4- and eight-arm MAW spirals in (a) forward and (b) reverse modes of operation	118
0.13.	Comparison of equiangular and Archimedean eight-arm MAW spirals average pattern	119
0.14.	Comparison of equiangular and Archimedean eight-arm MAW spirals impedance	119
0.15.	Four-arm compared to six-arm self-complementary MAW spiral phase center statistics, all modes, (a) shows mode 4, (b) shows mode 6	120

CHAPTER 1

INTRODUCTION

Multi-polarized spiral antennas were developed to provide compact frequency independent antennas for sensing arbitrary signals over multiple octave bandwidths. When the spiral antenna was developed in the 1950s [1, 2] the two negative features were recognized. Specifically, a significant loss because the spiral was difficult to configure without absorbing the backlobe, which inherently made the antenna very inefficient (gain is usually more than 3 dB below the directivity), and polarization blindness because the antenna inherently filtered all signals to the circular polarization arising from the spiral wrap. A sensor detecting a large variety of signals with the emphasis being detection independent of direction or polarization even if inefficient was needed. Poor efficiency only reduces the sensor's range, which is often an acceptable trade for accuracy and bandwidth. Polarization blindness limits the antenna even more since it introduces the potential for a signal to pass by undetected. Due to the limited available area to place antennas on most moveable articles (satellites, planes and ships), the geometry of a planar antenna is always of great interest, especially what capabilities it can provide without increasing weight or complexity. The first effective multi-polarized antenna solution to this challenge was the modified arm width (MAW) spiral antenna. At the time this research started, the MAW spiral antenna capabilities were thought to overlap completely with the sinuous antennas. This thesis demonstrates that this assumption is certainly not the whole story.

1.1 Motivation and Applications

Once a signal is detected by a receiver, many questions about the signal may need to be answered. First, is the fidelity of the signal sufficient (typically, the frequency of the signal will be needed to even evaluate possible distortion), typically wideband antennas degrade fidelity unless the signal is of similar bandwidth. Second, what is the signal's polarization, which is well answered by multi-polarized

antennas. Lastly, what direction was the signal's origin, requiring an antenna with pattern that is smooth and stable over both angle and frequency. Depending on the role of the receiver, the information above can be used to track, jam, or evaluate the signal to obtain more information. To do these applications well, within its predefined field of view, the sensor needs to be omni-directional and dual-polarized to avoid missing any signals. The sensor and/or receiver must provide additional processing capability to obtain direction and polarization. Once the signal is found, the information is far more useful if the location of the emitter is known as well and additional information may be extracted by more directive systems.

There are various technologies available to locate emitters, but one of the most useful and simple is angle of arrival (AOA) as done by a monopulse antenna. The spiral antenna supports this capability by providing two modes usually referred to a sum and difference, normally, but not always when the spiral has more than two arms. The ratio of the amplitude for these two modes without any other information provides the off broadside angle. With the additional measurement of frequency or a compensation technique for the dispersion, the rotation angle about broadside can be derived from the measured phase of this ratio as show in the Figure 1.1. Note that no direct demodulation of the signal is required in the detection. Only the quadrature voltage ratio is needed from the detection of the signal on two channels.

Figure 1.1 shows the coordinate system, where the angle off broadside is θ and the angle off the X axis in the XY plane is ϕ (antenna is at the origin). Because the planar antenna geometries all have an N-fold rotational symmetry based on the number of arms comprising the antenna it is very important to have a unique reference position, the equivalent of the XZ plane to base the rotational phase off in a physical realization of the antenna. The response of a typical spiral is shown in Figure 1.2, with mode 2 being divided by mode1 of (a) amplitude and (b) phase. The thesis will discuss the limitation of the off broadside sensitivity in the sensor because the accuracy of detection of θ degrades as θ increases due to the change in the relative patterns decreasing. Note how important it is for the response in ϕ to be unique as well, which is why only adjacent modes are used to eliminate phase wrap on the ratio. In some cases, the pattern will be distorted by additional modes some of which can be seen even for the spiral magnitude in Figure 1.2 (a) in the ripple. In Figure 1.2 (b), the phase should form straight lines through all off axis

angles for a constant ϕ resulting in a unique amplitude and phase pair for each angle pair in (θ, ϕ) . In practice, the mapping accuracy is degraded by polarization, frequency and poor control of unwanted modes. In Chapter 3, the effects of these error sources will be examined in detail. As the phase map shows there is about a 10° slope in measured phase at a fixed ϕ when θ is varied from 0 to 80° . More importantly, Fig. 1.2(b) show the phase clocking of 360° as the emitter rotates in ϕ about a fixed θ angle.

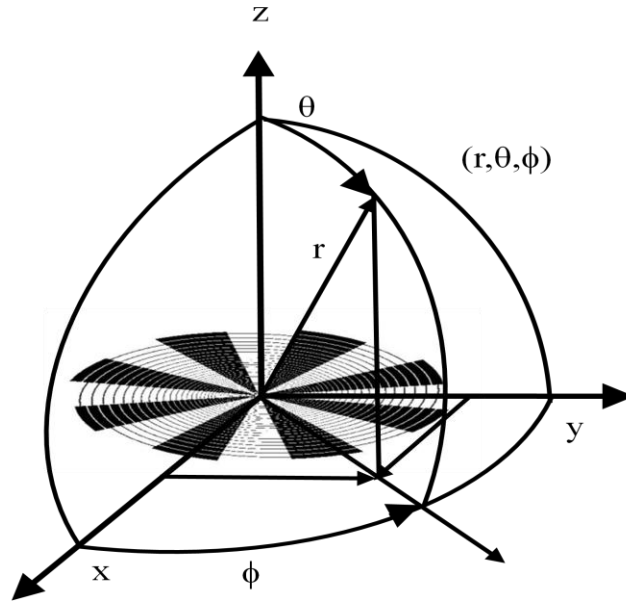


Figure 1.1: AOA sensing coordinate system.

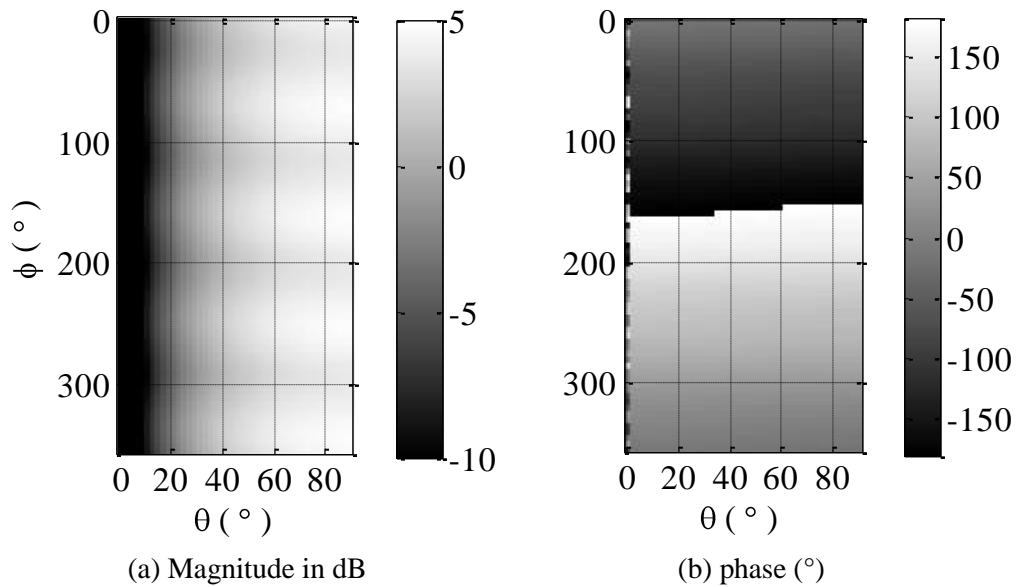


Figure 1.2: Response of the channel ratio for a four-arm spiral at $10f_0$.

Similarly, if a dual circularly polarized antenna receives a signal, the comparison of the two modes without knowledge of frequency, only the axial ratio can be measured directly. With the addition of frequency knowledge, the tilt angle of the received signal will also be determined but only if the AOA is also known approximately. Without AOA, the phase between the two modes is arbitrary because relative phase between mode 1 and mode -1 is an independent periodic function of both polarization and direction. In particular, the phase for each circularly polarized mode has one full cycle as it rotates around broadside, with the clocking determined by polarization. The result is between the phase ratio between modes -1 and 1 has two complete cycles for each rotation in ϕ at constant θ . This two complete cycle behavior also occurs as the emitter is rotated relative to a fixed angle in the sensor antenna pattern. Because of this, knowing the relative phase between the two sum channels is not sufficient information for detecting polarization. The outcome is that the dual polarized frequency independent antenna in order to solve the problem of polarization measurement already needs to be part of a system with AOA capability to get to a single value phase to tilt angle mapping.

This polarization detection problem does not occur in the simplified case of a loop and dipole antenna, which will provide orthogonal polarization measurement with a unique phase regardless of direction. This outcome is because there is not phase slope in either pattern, thus the tilt angle corresponds to the phase between the two antennas. However, these antennas do not have planar frequency independent equivalents and they are completely blind to broadside.

1.2 Frequency Independent Antennas

Frequency independent (FI) antennas are used for many sensor applications where the need is to detect a signal, not to necessarily provide a communication link. For conventional communication antennas the frequency and polarization are known, thus making the most important discriminators on the design efficiency and pattern coverage for a narrow frequency band. With FI antennas, the apertures are typically large to support as low a detection frequency as possible and often inefficient since they commonly use absorber to shape patterns and keep a low level of mismatch. The FI antennas come in many geometries, but for this thesis, we are only interested in those that can be flush mounted to a

platform, also known as planar. In this smaller group of antennas, we further restricted the interest in those with multi-polarized capabilities. The set that meet this requirement are sinuous [3, 4], co-planar log periodic [5, 6] and the MAW spiral [7]. Although the equiangular spiral can be dual polarized it inherently is not frequency independent in this mode of operation.

First, the term FI is used in many places in this thesis, and the interpretation as presented in [8, 9] is that the geometry of the antenna should be expressed as a function of angles only to make its behavior self scaling for bandwidths of a decade or more. Examples of this type of geometry include equiangular spirals and sinuous. The impedance of such geometries is known through Booker's application of Babinet's principle from optics [10]. However, the first departure from theory to realization is terminating the geometry as the principle only addresses the infinite sheet case. The termination is usually a resistive load if the size of the antenna [11] is to be minimized, otherwise the antenna will typically be much larger than the wavelength at the lowest frequency of operation to achieve stable impedance and pattern. This area of understanding the MAW spiral is of key importance because the antenna would probably be used where volume and area are critical and terminating it into a matched load would not work as discussed later.

The electrical size of the antenna can be limited to much smaller than its physical size by modifying the transmission line structure as the frequency increases. This design feature is often used in monopoles and dipoles where non-continuous bands are required. Specifically capacitive "traps" [12] are introduced to prevent higher frequencies from creating resonances across the full antenna aperture. This type of antenna modification also has a minimal effect on the radiation region by placing the "trap" outside that region. One of the first geometries developed demonstrating this capability for a planar aperture was the MAW spiral antenna. The analysis of the modulated transmission line behavior showed that for log-periodic dipole arrays, radiating elements could be decoupled from the input by use of the modulation on the feed line [13]. This work was then applied to spirals resulting in the MAW geometry. The MAW spiral geometry has an embedded self scaling circuit to prevent the effective electrical size from increasing beyond a designed size set by the modulations, but the modulations also help isolate the

radiation region from the input. The circuit, which will be called a bandstop hereafter, is the simplest bandstop filter [14]. It consists of a pair of quarter-wavelength sections, specifically cascaded low and high impedance sections that result in a reflection of the power back toward the input. This keeps the antenna much smaller electrically than physically once the bandstops are resonant. In the first patented MAW spiral planar geometry; this bandstop occurs at the 2λ circumference, because the antenna has four arms. In addition, if the modulation is chosen so that the amount of gap and metal in the transmission line are alternated and the period of the sections is the same as the number of arms then the geometry is self-complementary [15]. The visual method of determining if a geometric figure is self-complementary is interchanging the metal with air for the antenna and confirming the antenna looks identical upon a simple translation or rotation. This operation is called the complement of the geometry. Some of the geometries discussed in this thesis have equal area for metal and air, but the geometries are not self-complementary. This departure from self-complementary was determined to have more significant effect on the impedance than the one addressed by [16]. Of particular interest in this investigation was how key was the self-complementary geometry to the antenna performance, since it is usually the starting point in developing an FI antenna.

In this thesis, the MAW spiral geometry was compared with the sinuous geometry for relative merits particularly for the highest mode for which the beamformer has control. This evaluation had not been done previously. While investigations comparing the sinuous to the MAW for expected symmetric modes had been published [17], no conclusive reasons were established for the preference of the one geometry over the other. The marketplace has dictated a much broader use of the sinuous geometry based on the multiple vendors [18,19,20] and geometries available. Considering that, the patents for both antennas are held by the same company; there is no obvious reason for one design to become preferred, so a technical reason was evaluated as part of the first research activity. The result was that the sinuous typically outperformed the MAW spiral as a radiating element because of the inefficiency of the bandstop. No current advertisements of the MAW spiral antenna as a product were found in searches of media. Several other considerations that may have caused the increased usage of the sinuous include the

following: lower ohmic loss due to wider conductors for the same performance, less dispersion between the two antenna polarizations, and pattern symmetry between the opposite polarizations because the beamformer imposed the polarization sense. Etching the MAW spiral with a similar performance to the sinuous also requires higher accuracy. The resulting MAW spiral will only slightly reduce some of the pattern performance properties from the sinuous such as lowering oscillations in dispersion over frequency and in the tilt angle of the polarization. Probably as a result, research slowed on the MAW spirals, with a few claims in the 1990s [21-24]. These claims resulted in no improvements in either capability or performance of the antenna beyond what already was demonstrated in the results presented in [17], but do document that the antenna was being researched independently by several manufacturers.

With modern highly digital receiver designs [25-27], the reexamination of the MAW spiral geometry was appropriate, because in part it had never been determined if a spiral antenna that provided both polarizations and no bandwidth limit with patterns would be as well-behaved as an equiangular spiral antenna which is only capable of one polarization. The newest receiver configurations put less emphasis on beamforming by standard hybrid based beamformers and more on overall front end capability. This gives one a reason to investigate further the capability of geometries than may have been extremely hard to excite with conventional microwave beamformers, but straightforward with a digital sampling receiver. Additionally, while the basic operation of the antenna was shown in earlier research, the performance as a potential sensor was not investigated by patents or published technical papers [28-30]. If a clear advantage or negative of the MAW spiral antenna existed, it had not been recognized.

This thesis defines the limits of various portions of the MAW spiral design to ensure that if an application is desired, what criteria should be adjusted in the design for the application. Since the varied applications of the sensor make defining an all purpose optimum impossible, a more balanced approach to design investigation was taken. As an example, is it better to have a purer polarization or a constant impedance match. What is described in this thesis is the range of performance available with the MAW spiral geometry with sufficient resolution to indicate the range of values to search for the designer's potential solution.

1.3 MAW Spiral Antennas

MAW spirals belong to the family of frequency independent antenna geometries. They are unique because they combine a resonant circuit outside the radiation region with a conventional spiral structure in the radiation region. For the MAW spiral, the resonant circuit can be designed independent of the radiating properties of the element. In fact, if possible the collocation of the resonant circuit of the MAW with the radiation region should be avoided. This requirement is the opposite of the sinuous and co-planar log periodic antennas, where the resonant element of geometry is in the radiation region in order to work. While the bandstop circuit of the MAW spiral will still have some reflections, the shorter the bandstop is relative to wavelength in the radiation region, the lower the interaction with the antenna response. At the same time, achieving a high level of reflection to prevent modal contamination from current propagating the opposite direction is difficult if the circuit is also expected to pass frequencies below resonance with almost no reflection. The low growth rate required to make the reflection efficient also results in high dispersion and ohmic loss. The reflection does however show a continuous response over frequency due to the self scaling structure even when the expansion rate is large (>2).

A conventional spiral antenna has negligible reverse current component above twice its cutoff frequency for each mode due to radiation efficiency [31]. If terminated in a distributed load at the outside end of the arm the resonances are even further mitigated because the currents should not reflect off the termination. This response is why spirals are frequently investigated for acceptable pattern performance even well below their nominal cutoff. The cutoff frequency is determined by the number of wavelengths in the circumference for the equivalent mode, i.e. 3 wavelengths for mode 3 patterns, and even if the efficiency is poor, the pattern may be excellent. For a MAW spiral, this termination method will not work since the dual polarization is achieved by reflecting outside the radiation region. The problem then becomes designing a reflection that only causes small changes in performance from the behavior above $2f_0$.

A sinuous antenna has a resonance at the radius where element swing is sufficient to approximate a half-wavelength dipole, as does the co-planar log periodic dipole array although the sinuous can exhibit

reduced electrical size if the elements are highly interlaced [32]. The result of the sinuous geometry is that the radiating behavior is closely tied to the element geometry, but also that it does not need to be terminated, as it is already an efficient radiator.

1.4 Dispersion in Planar FI Antennas

An initial concern raised with spirals was the dispersion, which before investigating MAW spirals was known to increase over wide bandwidths if the other pattern performance parameters improved [33-35]. Dispersion in spirals has precluded some research in their potential for ultra wideband radar and broadband communications. For an antenna to have low dispersion means, it either radiates from a point over the bandwidth of interest (usually resulting in a changing pattern as is seen in many monopole designs) or uses a self scaling aperture of depth such as a Vivaldi horn. In spiral geometries, a traveling wave structure that varies in physical length with frequency is used to launch the field. The traveling wave structure due the delay growing exponentially with frequency results in the requirement for a non-linear device to compensate it. The MAW spiral in reverse operation is expected to have even worse dispersion than forward because the currents must reflect from beyond the radiation region, giving it the fastest change in path length over frequency. For all equiangular spirals, the dispersion increases inversely to the expansion factor. However, for signals of normal bandwidth ($< 2:1$), this dispersion is small [36] and can be neglected except near the antenna cutoff. Additionally, technologies exist today to compensate for dispersion when the transfer function is well behaved as it is with a spiral antenna. For the sinuous and log-periodic geometries, the dispersion is not always monotonic due to the resonances and can require a more complex transfer function corresponding to the period of the arm swing. In this thesis, the dispersion properties of the MAW spiral will be evaluated and correlated with bandstops.

1.5 Thesis Organization

This thesis is organized in five chapters as follows:

- Chapter 2, Dual Polarized MAW Spiral Antennas, the theory of operation and modeling of the antenna, as well as detailed results of a parametric study of the two parameters that can be varied under the basic geometry and their impact on pattern performance are discussed.

Impacts of less well described geometries including bi-layer, Archimedean and the scaling of the metal to slot ratio are described.

- Chapter 3, AOA in Four-Arm Spirals, investigates the third mode available on a four-arm MAW spiral and its performance relative to conventional spiral and sinuous antennas. The research demonstrated this mode is useable for modern AOA where the frequency is known and the pattern is available in a look up table.
- Chapter 4, Non-Self-Complementary Design Investigation, expands the parameters of the MAW spiral into non-complementary geometries evaluating the effect of period on the pattern and impedance. This investigation shows that antenna performance can be improved on various parameters by changing the period of the bandstop, in particular the polarization of the new mode, which is not controlled well by the parameters investigated in Chapter 2.
- In Chapter 5, Multi-Arm Capabilities, the performance of other arm counts except 4 are characterized for the MAW spiral with an arbitrary number of arms for possible functionality. This research demonstrates that the MAW spiral suite arising from N arms provides additional capabilities by controlling N-1 modes as long as they radiate efficiently.
- In Chapter 6, Conclusions, the results of the thesis are summarized and its contributions to the body of knowledge are specified. In addition, some areas for further research are delineated.

CHAPTER 2

DUAL POLARIZED MAW SPIRAL ANTENNAS

The literature survey of MAW spiral antennas had very little in published work outside the field of patents [7, 21-24], which were usually applied for primarily to protect company intellectual property. Because a patent is intentionally defining an idea legally, it rarely provides insight into whether and why the device works. The patent also reduced any interest outside the academic community in further research because the design is controlled for the next 20 years. What is presented in the literature is that in 1991 six-arm MAW spiral and sinuous antennas could produce dual polarized sum and difference patterns [17]. That paper was the most recent published information on the MAW spiral antenna until the research contained herein which began in 2005 [37], with the exception of a few paragraphs in general articles on FI antennas [29]. The first effort in the research for this thesis was to determine what the useful limits were for modulation versus the physically possible, in particular since the initial research only addressed elements with one surface preventing overlap of adjacent arms. After demonstrating that the antenna could be modeled with stable results, the next step was to set up a series of cases to populate the range of capabilities of the MAW spiral has by varying the modulation and expansion rate. Finally, the effects of dielectric and absorber backed cavity are incorporated to ensure that a model of a more practical antenna is considered.

2.1 Geometry of Frequency Independent Antennas

A brief familiarization with the geometries commonly used in FI applications is discussed first. The representations of the MAW spiral, the sinuous and an equiangular spiral are shown in Figure 2.1. The first two are dual polarized over the bandwidth that is limited by the detail of the feed structure and the physical size. The equiangular spiral that is not self complementary is the parent geometry to the MAW

spiral, with M being the ratio of arm width between the equiangular spiral with wide arms and one with thin arms. The termination for an equiangular spiral is not critical, except near cutoff where the termination may be improved by resistive loading to reduce cross-polarization and improve impedance.

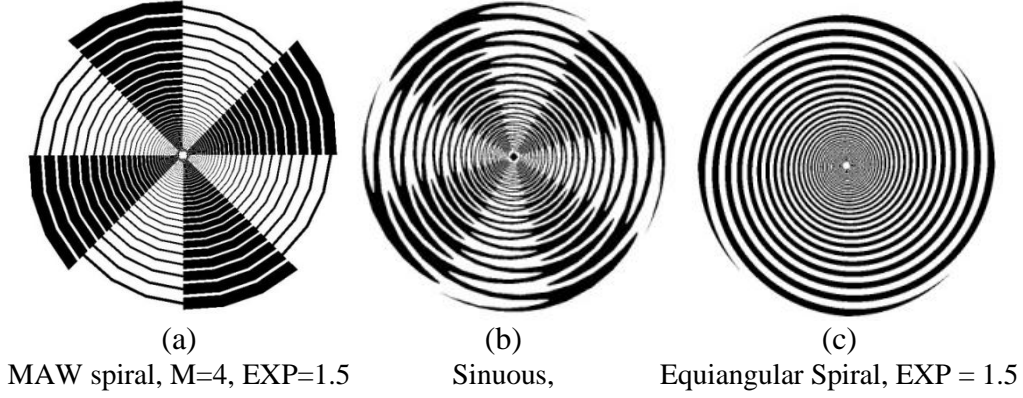


Figure 2.1 Studied four-arm FI geometries.

These spiral elements are then connected to a balun beam/mode forming feed. For this investigation, the balun was assumed to be a cluster of $50\ \Omega$ coaxial lines, one for each of the four arms [30]. The fundamental equation for the family of equiangular spirals [38] is first investigated by Descartes mathematically in Equation (1):

$$r(\phi) = r_0 e^{\alpha f(\phi)} = r_0 EXP^{f(\phi)} \quad (1)$$

Where r is the radius, r_0 is the starting radius, α = growth rate; $f(\phi)$ = modulation function of the arm, (equals ϕ for the equiangular spiral), $EXP = e^{\alpha 2\pi}$ is the increase in radius per one rotation, ϕ = rotation angle, not limited to 2π Arc length $s(\phi)$ for a particular r can then be computed by the usual calculus methods to be for the unmodulated spiral, where the starting radius is $\phi = 0$ as shown in Equation (2):

$$s(\phi) = \frac{r_0 \sqrt{1 - \alpha^2} (e^{\alpha \phi} - 1)}{\alpha} \quad (2)$$

Because the delay should be proportional to the arc length, the delay is expected to be nonlinear because the radiation region decreases linearly with frequency and delay is exponentially decreasing

causing a significant spread in the group delay of a wide band signal.

While equiangular spirals are commonly found with two arms, we only investigated MAW spirals with three or more because of the expectation to have at least one mode provided by modulation that the equiangular spiral did not generate. A two arm planar geometry does not produce a different voltage phasing across the feed point dependent on polarization. In the planar case, the two arms are inherently propagating opposite directions to get from the feed point to the radiation region. This property produces only one mode near the vertex. The antenna must have additional conductors to distinguish incident polarization. The two-arm spiral does produce excellent polarization rejection for fields rotating opposite to the spiral wrap, showing even the simplest spiral element provides polarization filtering.

In particular, this chapter investigates the four-arm geometry for MAW spirals because it is easily fed with a beamformer composed of commonly manufactured components – 180 and 90° hybrids [39]. Although the elements above could be fed with a matching balun to transform a 50Ω port to the antenna characteristic impedance [40], the mismatch losses are not that significant to overall performance, expectation is about 1 dB for a return loss of 6.8 dB. Making a balun would have been useful for the dual polarization evaluation, but difficult to fabricate into a center fed structure.

The geometries of the sinuous and equiangular spiral will be more carefully compared in Chapter 3 to the MAW spiral, but visually the differences between the three structures are noticeable as seen in Figure 2.1. The apparent first requirement for a dual polarized FI antenna is to have a conductor by inspection to cause current to flow in two directions on the element. The sinuous does this flow using arm swings, whereas the MAW spiral accomplishes the same result with reflective transmission line sections. The fourth geometry, coplanar log-periodic, not shown, accomplishes dual polarization by superposition of two orthogonal log periodic dipole elements which inherently has current flow in both directions at each radiating element [41 42].

To model numerically any of these antennas except for the equiangular spiral will require a very fine mesh because of the embedded resonances from the current flow. While most finite element algorithms have excellent meshing capability, they do not perform well on creating the symmetry

required for an antenna composed of elements that are identical except for rotation. This is due to two modeling problems. First, the mesh detail of the launch must make each arm sufficiently symmetric to create good cancellation with high coupling between arms. If the launch is done inaccurately, it causes significant errors in the prediction of the cross-polarization. Second, the sheer size of the problem becomes too large to do an accurate full volumetric model over frequency resulting in significant pattern differences between the arms known to be theoretically identical. While not always a serious limit to pattern prediction, imposing symmetry on the problem does make the solution easier to inspect for convergence.

Design development was divided into four activities, consisting of developing robust models in FEKO [43], a method of moments modeling tool, followed by validating the model results in HFSS [44], a finite elements tool based on tetrahedral elements. Next, the parametric study of modulation and expansion factor are performed, while the validation of the results with a working prototype is performed at the end. The method of moments (MoM) simulation was chosen as the best tool for this problem because of the combination of using a free space Green's function for pattern calculation and having no need for materials in the initial parametric study thus minimizing the model size. Using the FEKO solver optimized the computational time sufficiently to perform swept frequency and solution convergence evaluation of the design. Although results were run within the simulation containing coaxial launch and dielectric material, the emphasis for most cases was to determine that each geometry's behavior was known and stable. To simulate the MAW accurately, the mesh was held constant at approximately $\lambda_{\max}/8$ excepting the fine structure surrounding the feed point. Part of the reason that the large runs were needed was to evaluate the antenna's sensor performance which requires much more information including complete patterns, stable transfer function over frequency because of the possibility of narrow band resonances and complete input response including coupling.

2.2 Theory of Operation

The spiral relies on the delay due to the growth of the spiral to bring adjacent arms into phase at the resonant circumference resulting in radiation by creating a current ring at the circumference where the

current is in phase between the adjacent arms [45]. An example of this phasing would be if mode 1 is desired on a three-arm spiral, the phase at the feed point is 120° between adjacent arms, however these adjacent arms will have no phase difference at a one wavelength radiating circumference because the lagging arm will travel an additional -120° to arrive at the same ϕ location. The number of cycles in phase at the radiating circumference where the in-phase condition occurs corresponds to the mode and the progression of the phase either clockwise or counter clockwise determines the polarization. This property allows one to determine the nominal polarization of any spiral by visual inspection, with a right hand increasing wrap being right hand circularly polarized. Interestingly, if the current flows in the reverse direction (starting from the outside for instance) then the polarization will flip for the antenna [46]. Unfortunately, this solution is limited in bandwidth by the number of arms and the electrical size of the antenna. For the four-arm case, the limit will be slightly less than 3 times the cutoff frequency depending on dielectric and acceptable polarization level. For the MAW spiral, a method was developed to improve this bandwidth while keeping the antenna a spiral. The introduction of self scaling bandstops made the geometry dual polarized while maintaining frequency independence. The bandstop is a combination of two transmission line sections one high and one low as show in Figure 2.2. The combination is placed on each arm to maintain symmetry and at the same clocking on each arm. The angle occupied by each impedance section is π/N (N for the number of arms). The spacing is done to keep the spiral self complementary as well as to ensure rejection of modes greater than $N/2$.



Figure 2.2: Illustration of a Bandstop for a four-arm MAW spiral antenna.

2.2.1 Bandstop Design

The optimal design for the bandstop if only maximum reflection is desired is one where the characteristic impedances of the two sections are as different as possible to make the reflection coefficient almost unity. This situation would be when the modulation is largest, which is why the initial investigation of two-layer geometries to further increase the impedance disparity was performed. Modulation (M) is defined as the ratio of the cross-section width of transmission lines at the transition between the two impedances. If the frequency response neglects coupling in the bandstop region of this geometry, it can be approximated by the transfer matrix of transmission lines for a two port device as in Equation (3). This response is commonly used to create bandstop filters, as above the resonance the majority of the power reflects back in the direction of propagation. Cascading Equation (3), the reflection and transmission of an individual bandstop can be calculated by converting the ports back to local impedance.

$$[\underline{A}] = \begin{bmatrix} i \cos(\beta l) & -iZ_M \sin(\beta l) \\ -i \sin(\beta l) / Z_M & i \cos(\beta l) \end{bmatrix} \quad (3)$$

where Z_M is the characteristic impedance of the section of coplanar waveguide-like (CPW) transmission line [47] as shown in Figure 2.3. We know that the mode chosen is not critical because the ratio of impedances is independent of the mode [16]. To obtain the ratio corresponding to M , one must go to the points at $M/S < 1$ and $M/S > 1$ such that the ratio of the two values equal M on Fig. 2.2. Note, the transmission line structure of a MAW spiral is not a true CPW (not surrounded by a ground plane on both sides, just the other spiral arms) and there is some secondary coupling to adjacent arms that will modify the results. What is being shown in Fig. 2.2 is the basic curve that would result for the arbitrary MAW spiral and mode when one wishes to calculate the effectiveness of a bandstop. If one cascades two of these sections together the resulting reflection term can be determined for the quarter wavelength case straightforwardly as in Equation (4). When Γ is near resonance the reflection coefficient of the bandstop becomes:

$$\Gamma = \frac{(Z_M^{ncomp1})^2 - (Z_M^{ncomp2})^2}{(Z_M^{ncomp1})^2 + (Z_M^{ncomp2})^2} \quad (4)$$

where, $Z_M^{ncomp1,2}$ are the characteristic impedances of the first (high or low impedance) and second (low or high impedance) complementary sections. As indicated, order does not matter and this case is looking at two sections of similar length. If another pair of sections is added to this sequence, the reflection reaches -2.4 dB for the transmission line, when it is only -6.7 dB for one section pair if the arm modulation is 4. With a modulation of 8, the reflection improves to -1.1 dB with two section pairs still allowing a transmission of -12.3 dB. Obviously, the performance of the bandstops including coupling and variable lengths due to expansion factors will be important to the modal purity of the resulting pattern. Defining good performance for a mode generated by a bandstop would first be in comparison to its normal or forward operation pattern, and second the pattern of an unmodulated spiral with the same expansion factor. The parametric study has shown that the performance of a MAW spiral will be very similar in modes ± 1 for a modulation of 8 and an expansion factor of 1.5. Neither of the four-arm MAW spiral modes will have the modal isolation of an equiangular spiral antenna for the same growth rate, but the antenna will achieve two polarizations in the same aperture size that the equiangular has only one.

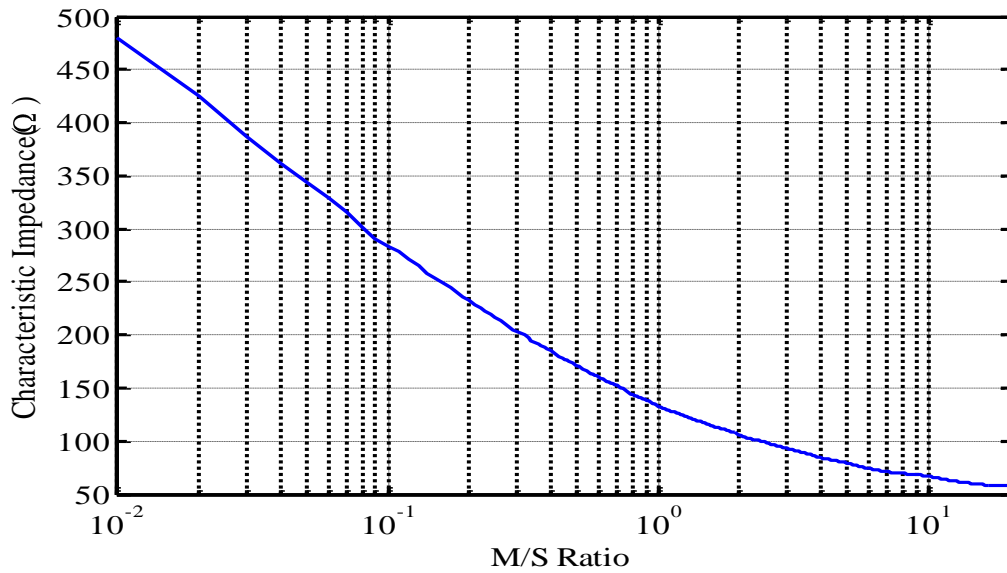


Figure 2.3 Impedance property of coplanar waveguide (Metal “M” versus slot “S” width for CPW).

The chosen location of the bandstop in the design is such as to ensure a self complementary structure to minimize the impedance effect of the bandstop. From [16] the impedance of any geometry that is self complementary is expressed as a relationship between the number of arms and the mode in which the arms are excited. However, the mathematical mapping requirement is that the complementary image of the structure is the same ensuring that impedance can be mapped back to a simple radial structure for which the impedance is known in Equation (5) [10],

$$Z_m^{comp} = \frac{\eta_0^{1/4}}{\sin\left(\frac{m\pi}{N}\right)} \quad (5)$$

Where, m is the mode of operation, N is the number of arms, η_0 is the characteristic impedance of free space, Z_m^{comp} is the self-complementary modal impedance derived for mode m of an N -arm self-complementary antenna as evaluated in free space.

$$Z_m^{ncomp} = Z_m^{comp} \frac{Z_{nc}}{Z_c} \quad (6)$$

Where the mapping to a self-complementary geometry is a ratio with the following variable descriptions [48]. Z_m^{ncomp} is the non-complementary impedance for mode m with an arbitrary ratio of metal to non-metal. Z_{nc} is the non-complementary impedance for the transmission line of the antenna. Z_c is the self-complementary impedance. Z_m^{comp} is the impedance for a self complementary structure computed using [16].

$$Z_m^{comp(\epsilon)} = \frac{Z_m^{comp}}{\sqrt{\epsilon_{eff}^{comp}}} \quad (7)$$

in which ε_{eff}^{comp} is the effective loading of the dielectric substrate on the coplanar self-complementary structure. While overall, dielectric loading could be a way to improve bandstop performance, it also results in scaling the antenna away from free space and making it a less efficient radiator by the same scale factor resulting in poorer pattern performance or modal isolation.

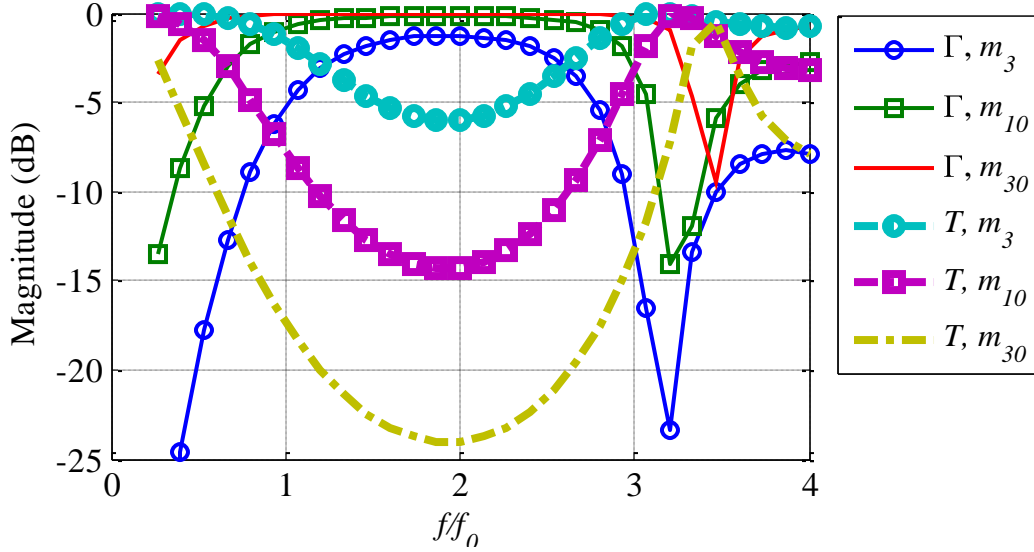


Figure 2.4: Reflection and transmission of bandstop section modeled at 2λ radiating ring circumference. T is transmission through the bandstop, Γ is reflection from the bandstop, m_n is the modulation of the spiral arm.

Unfortunately, increasing the modulation does not scale directly to characteristic impedance. To achieve a reflection of 0.97 or suppression of mode 3 to -20 dB requires a 30:1 modulation ratio. The reflection and transmission coefficient responses of these lines computed using FEM code Ansoft HFSS are shown in Figure 2.4. For usable expansion factors, only one wrap of the arm will be near the resonant length. If the expansion factor is extremely low then the spiral can have significant ohmic losses. However, the bandstop performance will improve because the rejection of the lowpass will be increased by the cascaded response of multiple bandstops (more bandstops in the reflection region with a lower expansion factor). If the region where the bandstop will be useful on a four-arm MAW spiral is between the radiation ring for mode 1 and mode 3, then the number of bandstops can be determined from the expansion factor. The expansion factor is equivalent to the increase in size for each rotation then at best case a MAW spiral with growth of 1.5 produces a total of 2.7 wraps in this region. This number of wraps

would correspond to 10.8 bandstops, although obviously all are not near resonance because the frequency bandstop of each is shifted approximately 30%. The more realistic value for this expression would be ≈ 3 bandstops as shown in Figure 2.4. The point from above in the derivation of the bandstop is that it is independent of the phasing between adjacent arms, the local impedance mismatch of the bandstop is the same. This issue is important because the phasing goes through a half cycle between the adjacent arms as the current travels from the mode 1 to mode 3 radiation ring.

The practical limit for slow expansion with high modulation allows not much more than 3 bandstop sections per arm in the bandstop region to reinforce constructively the reflection based on the limit for conventional etching tolerances and the changing delay for each section. Note that the use of the coplanar transmission line model for the circuit is consistent with the operation of the antenna, where each arm is fed with a different but radially symmetric potential from the adjacent arms. When the adjacent conductors have opposite polarity, as in the mode 2 case for a four arm the impedance structure at the feed is equivalent to conventional coplanar waveguide. The expected impedance of a coplanar waveguide is generalized for planar N-fold structures [48]. This case is for straight transmission lines where the phasing between arms is constant on a support structure similar to the MAW spirals considered here. The stability of the solution over frequency is excellent.

The self-complementary geometry occurs in equiangular spirals except when arm width to gap ratio is intentionally altered as with slot spirals and even then is easily addressed by Booker's principle. With the MAW spiral geometry, the period must be a least common multiple of the number of arms to provide a self complementary image of the geometry. Otherwise the gaps are staggered because the metal sections do not align rotationally. This staggered geometry is not self-complementary because if the air gap and the metal were exchanged the resulting geometry could not be aligned to completely overlay the original geometry. Thus, the geometry normally used is one in which the modulation period matches the number of arms, because that choice is consistent with maximizing the useful modes of the spiral. An example is if the spiral has six arms, and the modulation has a period of six around the circumference, then the reflection occurs at mode 3 allowing the designer to use modes ± 1 and ± 2 , if the period was three

then only ± 1 would be available and the antenna would not be self-complementary. If a modulation period of 12 was chosen, no reverse modes would be created since the bandstop was at mode 6 radiating circumference. The conclusion for the four-arm geometry would be better patterns occur using low expansion factor, modulation ratio (m) of at least four and a modulation period of four.

2.2.2 Dispersion in FI Antennas

Dispersion in MAW spirals arises from the transmission line feed varying exponentially in length as the frequency changes linearly. Dispersion is defined as the frequency derivative of group delay or equivalently group velocity. Because the MAW spiral is functioning similar to a conventional waveguide [49] with a cutoff and a rapidly changing delay above cutoff, it will be much more dispersive than a ridged horn, but have the advantage of a fixed phase center in space, which is extremely useful for reflector feeds. With the addition of the bandstop, the reverse modes are even more dispersive because they travel through the radiation region twice to a reflection point of changing displacement beyond due to frequency. The response over frequency however is monotonic because the electrical separation between the bandstop and the radiation region is shrinking exponentially based on the arc length of the spiral arm as frequency increases, not oscillating like a sinuous antenna due to the frequent direction changes of the arm current. If the bandwidth of the signal is less than 2:1, then the dispersion can be reduced by applying a delay line to compensate for the difference between modes. The individual mode will still have some dispersion over the 2:1 bandwidth and it decreases with larger expansion rates. Figure 2.5 shows the delay of a MAW spiral over frequency versus the other two common cavity backed FI antennas. Dispersion can be reduced by sacrificing beam symmetry by increasing the expansion factor. Because the fidelity of the received signal is typically a communication antenna concern further evaluation of the impact of the spreading of a pulse will be left to a later section. An additional concern with MAW spiral antennas is that the modes are dispersive relative to each other. This means that the signal distortion in reverse operation will be more significant than the forward operation.

As Figure 2.5 shows, the delay for the MAW spiral mode -1 has almost 3 times the delay of the equiangular spiral in mode 1. The spiral and MAW spiral antenna have nearly identical delay for mode 1.

Interestingly, the sinuous shows a larger delay even though the geometry appears to have a shorter distance to go physically as shown in Figure 2.1. As mentioned before, while the sinuous could be tuned to have an identical delay to the spiral, its delay is controlled by the expansion factor of the arms (1.24 estimated from the growth for each arm period) and the total swing of the arm (135°), for the case shown. This means the sinuous arm that was modeled cycles through the radiation region slightly less than twice as fast as the spiral, and one can expect it to have 675° for every 360° of delay for the spiral. Figure 2.6 shows this geometry period clearly, as there are always just fewer than 2.5 cycles on the sinuous arm per spiral wrap. This logic does explain the delay difference shown in Figure 2.5, even though the arm is wide and appears visually shorter.

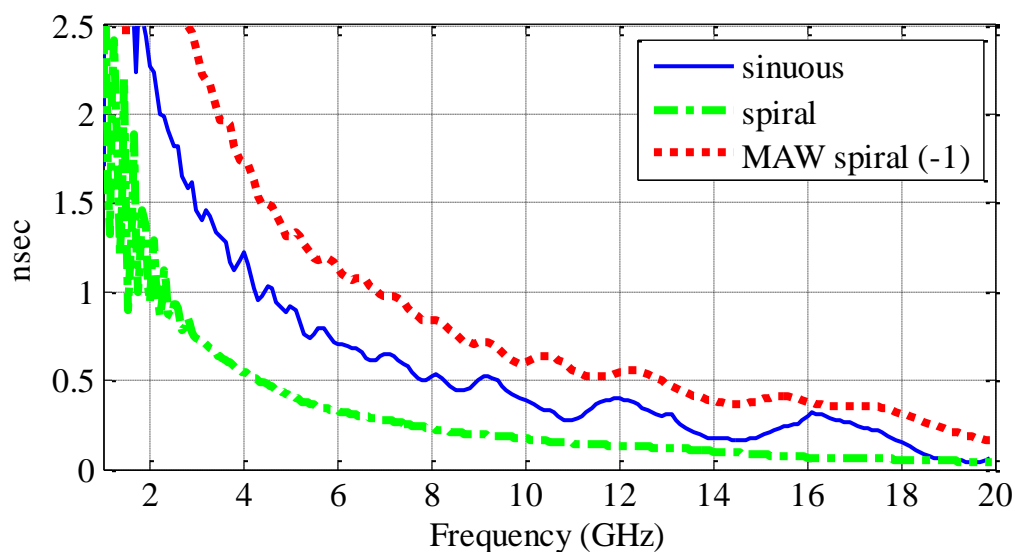


Figure 2.5: Delay of the modes of the three different FI antennas.



Figure 2.6: Overlaying the sinuous and spiral geometry to correlate expansion factors.

The parameters that were thought to be important for maintaining a reasonable comparison for these three different geometries were having the antennas have similar expansion factors. With the equiangular spiral this assumption was reasonable because the same expansion factor is used. For the sinuous however, because the equation is different the expansion factor seemed too high and instead a working geometry was estimated from a sample of the commercial literature. Because of this design choice, the delay of the sinuous is larger. Figure 2.7 shows that the delay is not the whole picture, the dispersion, which is the derivative of delay, is highly oscillatory (the vertical scale is for group velocity) for the sinuous and MAW spiral. This relationship is why for the data set the calculation became unstable as the antennas approach cutoff due to the ringing of the current on all the elements. Above that region the dispersion decays, and the periodic structures can be seen imbedded in the overall response. The equiangular spiral is smooth because it has no internal reflections above about twice the cutoff frequency.

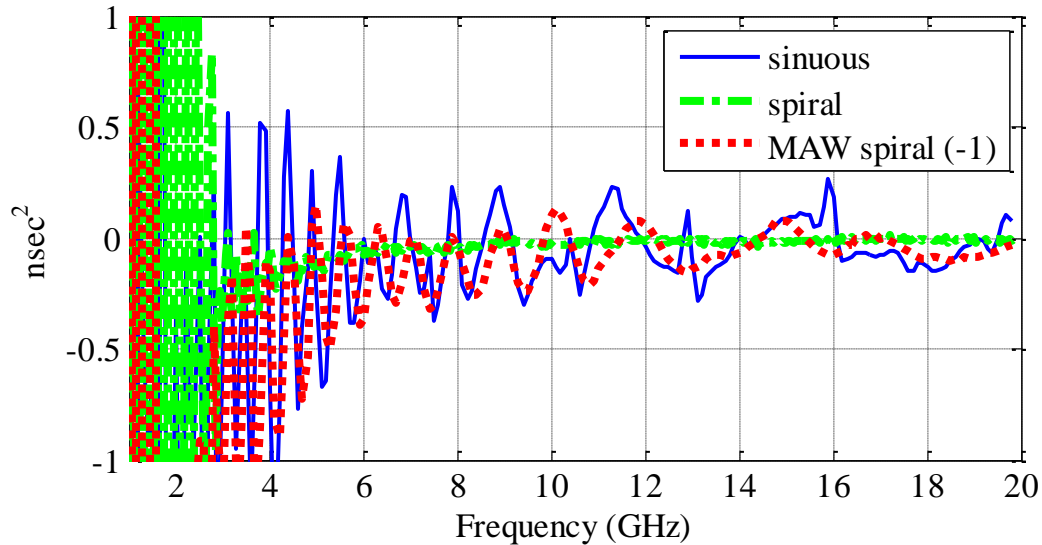


Figure 2.7: Dispersion (relative group velocity) of planar FI antennas.

The current of the equiangular spiral is inversely proportional to the gap between the arms, so since the gap increases exponentially and the impedance is constant the current decreases exponentially. This current behavior makes it harder to present the arm current behavior graphically, especially for MAW spirals that locally vary the impedance as well. For an Archimedean spiral, the current still decreases due to the voltage differential decreasing between arms as they approach the radiation region.

The Archimedean arm width/gap ratio is constant from the feed region to the radiation region. As the Archimedean spiral grows the current still decreases from the feed point to the radiation region, after which the current further decays quickly due to radiation losses. As long as the arms are properly terminated the spiral behaves as if the geometry is infinite and no reflections occur back to the feed for the unmodulated spiral, ensuring both low cross-polarization and no impedance ripple. However, for MAW spiral antennas, the current must flow both directions on the arm to at least the bandstop region. This situation creates the potential for the input impedance to change over frequency due to the phasing of the reflection. The only way to reduce this ripple is to reduce the current reflected back through the radiation region to the feed of the MAW spiral. Several runs of different growth rates indicated that while pattern symmetry and efficiency improved with reduction in the expansion factor, no practical method by geometry alone would reduce the reflection. Figure 2.8 shows the MAW fed first as a single arm, then in both forward and reverse mode as well as in mode 2 for completeness. The currents can be seen to increase by several dB in the bandstop region. The different radiating circumferences marked correspond to λ and 2λ in free space. Note that the current increases on the low impedance sections as expected. The 50 dB scale was used for all the geometries for consistency.

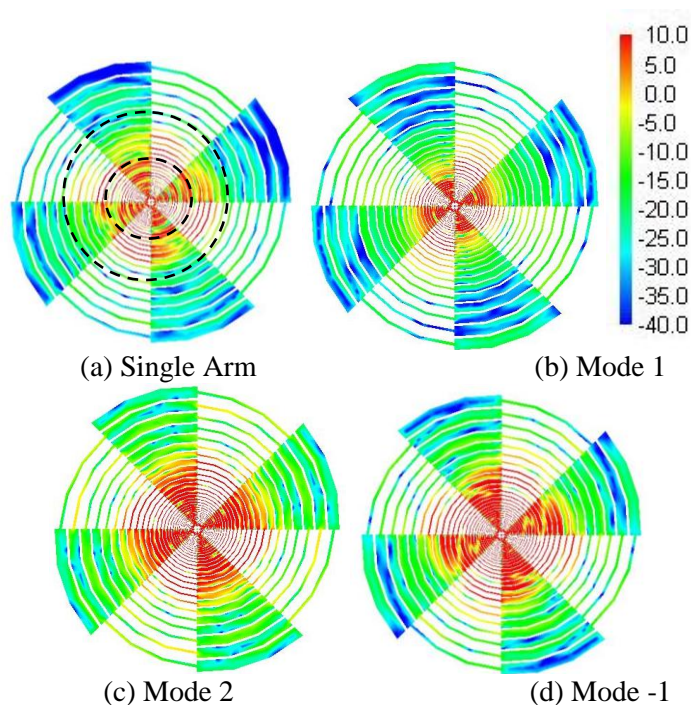


Figure 2.8: Currents for single arm and three modes of operation at $4f_0$.

While the details may be hard to extract from the above representation, it is apparent that the currents extend into the radiation region for mode 3 in all operational modes including mode 1. In addition, for mode 2 the currents are significant even beyond this region. Most importantly though is that the strong currents at large radius are more significant in modes 2 and -1 and in mode 1, where the bandstops should create current minima and maxima at a spacing of $\lambda/2$. As can be seen in the clearly in Figure 2.9 the local peak in current is at the resonant bandstop transition. Although the low impedance section will have less current per area, in the bandstop region the wraps have much less current in their interior and high currents at the transitions.

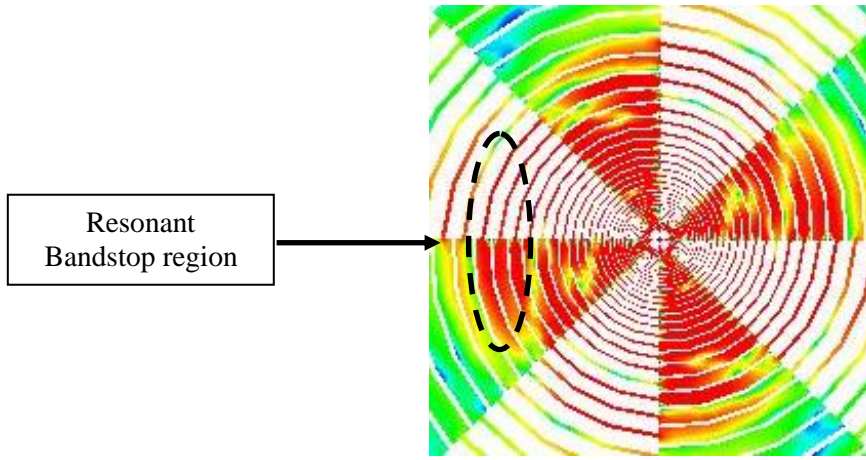


Figure 2.9: Bandstop current detail on the MAW spiral.

As mentioned in the description of the bandstops, the modulation period is chosen primarily to be self-complementary, but even then the frequency independent impedance is still well behaved when the modulation exceeds 150%. There is a pronounced faster ripple for the antenna impedance for the over modulated case, but even when the modulation was reduced to self complementary with a small separation between the arms out of plane, the impedance was altered by the same magnitude and frequency. The offset between the opposite conductor arms was $0.0003 \lambda_0$, which would seem to be too small to explain the observed phenomenon, but there were no other modifications to the model. In addition, since the modulation ratio of the arm was varied and produced the same ripple in magnitude and frequency, it appears that the MAW geometry is quite sensitive to planarity. Further details will be provided later in the chapter. Although the over modulation does not change the impedance, the bandstop

created by this geometry shows actual degradation in polarization performance from the 8:1 modulation with the same growth rate for rejecting mode 3 at the lower end of the frequency band. Even well above the cutoff frequency only similar performance is produced by the modified MAW spiral, producing no conclusive reason to attempt a bi-layer fabrication. The faster embedded ripple in the self-complementary impedance shown in Figure 2.10 is consistent with the total arc length of the spiral.

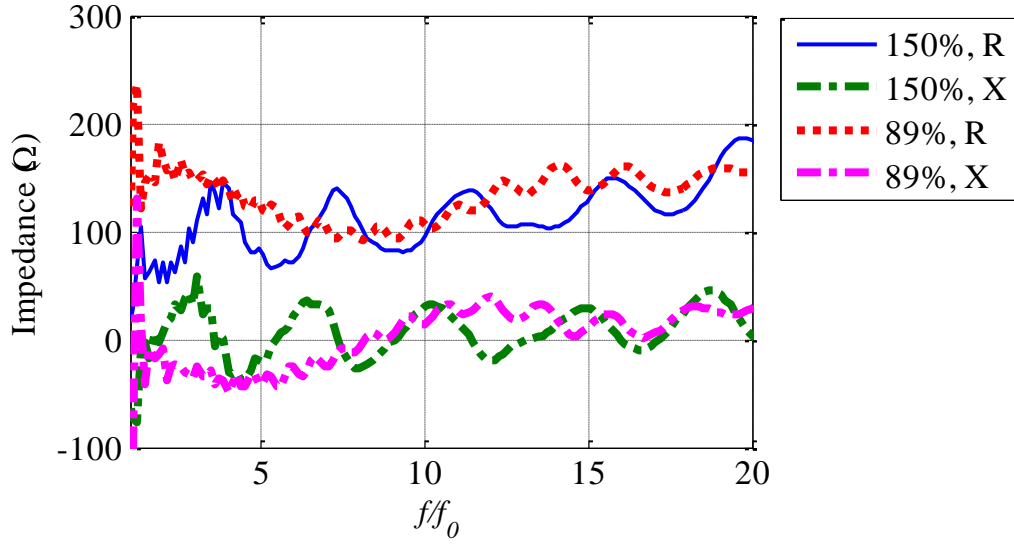


Figure 2.10 Input Impedance of a MAW spiral with modulations of 89% (8:1) and two layer of 150%

2.3 Modeling

Modeling of the MAW spiral antennas by MoM has several challenges. First, the computational expenditure of the cavity and dielectric in the model dwarfs that of the radiating element. This is because these surfaces are automatically larger than the physical element. In the case of dielectric modeling, the model will require additional basis functions for magnetic currents. Including them in the model quickly grows the scale of the computation. In addition, to excite properly the antenna from a coaxial interface requires the addition of a balun and beamformer. These devices are best handled separately by use of superposition methods to reduce computations in the solver tool. Especially because the tool repeats the entire matrix factorization on the geometry of each port, the inclusion of a balun would be inefficient. One negative to this approach is that the model shows more sensitivity to the launch geometry symmetry than the real hardware would. Simplifying the problem by removal of the balun makes the power division

more sensitive to the mesh than if the interaction is at a generator several wavelengths away. The modeling of a MAW spiral is also challenging due to a combination of fine and coarse geometric details, and the necessity to operate over multiple octaves while containing many narrowband rejection regions. The first objective is to ensure the mesh provides numerically stable and accurate results. To do this, several examples were run with the emphasis placed on the four fold symmetry of the mesh. The MAW spiral geometry ensures that the far-field must be rotationally symmetric when ideal phasing and amplitude is applied. This is important because the theoretical broadside cross-polarization (also co-polarization for modes higher than ± 1) must be zero for a symmetric geometry and ideal beamformer. The nominal case, uses a mesh triangular side length of less than $\lambda/20$ at the highest frequency. However, the geometry discretization results in slightly different triangular elements on antenna arms. When the symmetric mesh is enforced by the rotation of a single, already meshed arm, the broadside cross-polarization drops to the value set by the computer's accuracy (about -80 dB here). Figure 2.11 demonstrates the effect of mesh asymmetry associated with an implemented meshing algorithm in FEKO.

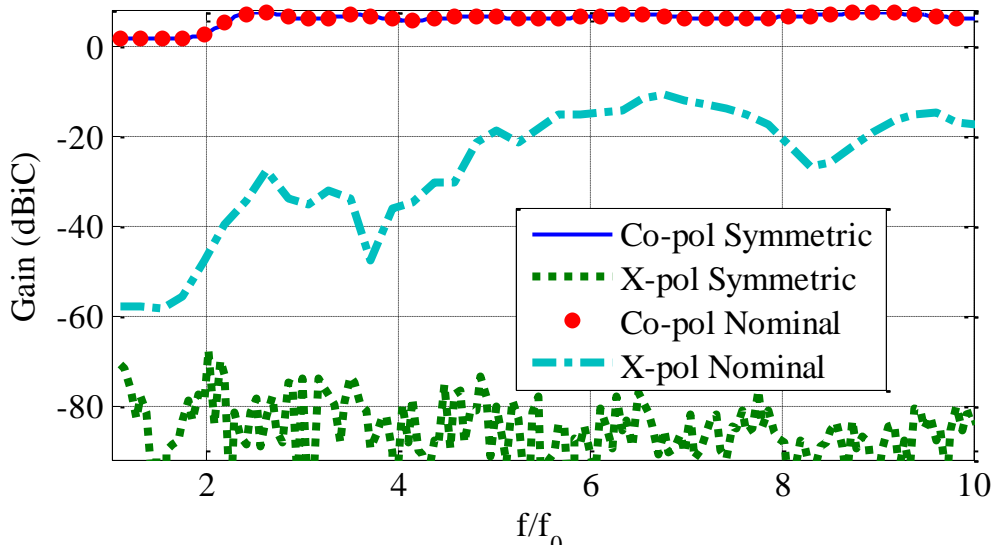


Figure 2.11: Effects of mesh asymmetry on broadside gain for MAW spiral with the growth of 2 and modulation of 4 that is fed with wire probes, ‘nominal’ refers to the automatic mesh by FEKO, ‘symmetric’ refers to the enforced mesh symmetry.

The use of the automated meshing tools does not enforce mesh symmetry even though it will impose a finer mesh around the feed region. As seen from Figure 2.11, the antenna needs to have the

symmetry imposed by using the same mesh on all arms that is obtained by rotating a single meshed arm. This technique is easily done in the MoM solver since it does not refine the mesh during the solution process nor have to mesh non-conductors if they are planar. Use of partial differential equation based solvers such as HFSS and CST for accurate modeling of MAW spirals is more challenging as the implementation of 3-D mesh symmetries requires tools to be developed to address specifically this symmetry. Experiments conducted with FEM code with continuous mesh refinement and increased order of expansion degraded the accuracy of the solution due to the loss of symmetry. Unfortunately, none of the commercial solvers takes advantage of the rotational symmetry of the spiral as of yet.

In MoM solver, the MAW spiral was excited with different excitation techniques including edge (plate), wire and coaxial feeds. There were no appreciable differences in impedance or far-field performance. This result was expected because if modeled correctly, the feed point should be too small to affect the spiral impedance or pattern as long as symmetry is preserved.

2.3.1 Finite Element Modeling

Finite element modeling of the MAW spiral was used to confirm MoM model outputs, in particular the antenna impedance. FEM also allows the introduction of an absorber loaded cavity and substrate with minimal additional computational load. The mesh is only slightly denser due to the dielectric other than free space. The basic problem is that unlike the MoM solver the volume needs to be meshed to get the antenna to solve. However, the initial runs of the solver only would allow one run at a single frequency in the time that the MoM would provide a swept frequency result, which extremely limited the solver usefulness for the parametric investigations. This problem in addition to the symmetry problem described above made it difficult to make the antenna representation behave, as it should by inspection from knowledge of the theory underlying spiral pattern synthesis.

The alternate time domain tool (CST) was not investigated although it has the potential to solve the entire model in one pass [50]. Some difficulties with the details of the feed point structure are expected to arise due to the cell size being not as flexible as FEM. CST also has a finite element solver similar to HFSS. With the problems already observed with the HFSS FEM, none of the discussions with

the vendor yielded reasons for further investigating CST.

2.3.2 Dielectric

The dielectric loading of the antenna was treated as a secondary effect because previous experience with spirals had shown that best pattern performance and match arose from designs that minimized dielectric parameters (permittivity and thickness). Even then, the initial modeling showed a strong coupling of the performance when the material exceeded an effective thickness of $\lambda/25$ [51]. This result was found initially by inspection of the results for a material of 0.08 mm. When the dielectric thickness exceeded the above value the results of the loading were observed in both the model and the measurements. Further simulations showed the change scaled with thickness and permittivity. In addition, the resulting pattern symmetry shifted with frequency for an element that was held constant. An attempt to avoid this problem was made computationally by imbedding the antenna in a symmetric dielectric with the same thickness on both sides and neglecting the fabrication gap. However, the higher level of pattern deterioration was observed, implying the problem was the dielectric loading itself rather than the field symmetry on the surface. Importantly, this result demonstrates the MAW spiral is a poor candidate for miniaturization by dielectric loading, if the arm termination was not a sufficient reason already. In our second fabrication the dielectric constant was lowered and the thickness reduced to maintain a similar sized element with less loading due to the substrate.

2.3.3 Cavity

The absorber loaded cavity of the MAW spiral or any dual polarized antenna is an unavoidable performance degradation source. First, as a minimum, one loses 3 dB by absorbing the backlobe, although theoretically this loss could be mitigated by cooling the cavity since there are no desired emissions from the cavity. However, the resulting sensor would still have the same front lobe pattern as the free space version, with gain of 6 dB instead of the 9 dB of a reflective cavity. The real performance improvement in G/T would be in the noise temperature of the antenna being reduced by up to 3 dB depending on the scene. Second, moving from the thought experiment to a real world implementation, the cavity absorber will typically be the same temperature as the antenna element making the effective temperature of the

antenna within 3 dB (only one lobe sees the ambient temperature) of the mounting structure. This is not the case with most sensors, which try to minimize the resistive and backlobe losses of the antenna. The cavity is desired to be as small as possible for packaging, although optimal performance will be with the antenna being loaded like free space so both hemispheres are symmetric. The usual compromise is to have the cavity sufficiently large that the element is entirely inside the cavity, with the depth being approximately $\frac{1}{4} \lambda$ at the lowest frequency of operation. While this approach is certain to raise cross-polarization and modal contamination in the antenna pattern, it is a realistic implementation of the absorber backed cavity based on dimensions from multiple manufacturers. In order to model this structure efficiently, the cavity was normally treated with a infinite single layer of Perfect Matched Layer material, mathematically set for the first order to $\epsilon_r = \mu_r = 1 - 2.7i$ [52]. Although this response does not represent the dielectric properties of an existing material or even the theoretical concept of a reflectionless material in all directions, it is the suggested best compromise computationally. Two problems with this modeling approach are that due to the infinite layer of material, the backlobe results of the antenna are meaningless. However, overall the representation of the antenna should be similar to an antenna mounted in free space that is entirely contained like the commercial components. In the version of FEKO used for these simulations, the model could not process the cavity, as a simple waveguide port below cutoff so investigating this approach for terminating the cavity model was not addressed.

2.3.4 Archimedean Geometries

Figure 2.12 shows the Archimedean [53] version of a MAW spiral. While not specifically described by the patents as an alternative geometry to equiangular, there are no specific reasons it is not an equally suitable candidate for a modulated arm design. The major difference as shown is that as the frequency decreases the arc length increases faster than an equiangular antenna with the same number of circumferential wraps. If one examines the basic spiral geometry regardless of growth method (Archimedean, equiangular or some hybrid of the two) the capability to radiate orthogonal polarizations requires the direction of propagation on the spiral to be in the opposite direction for the second polarization. For two arms the sum mode is degenerate because the phasing is the same for both right and

left (0 and 180°), unless non-traditional feeding techniques are utilized or the structure is not planar [7, 54]. For three arms and more, the two modes (forward and reflected) can be created by straightforward phasing techniques regardless of expansion method.

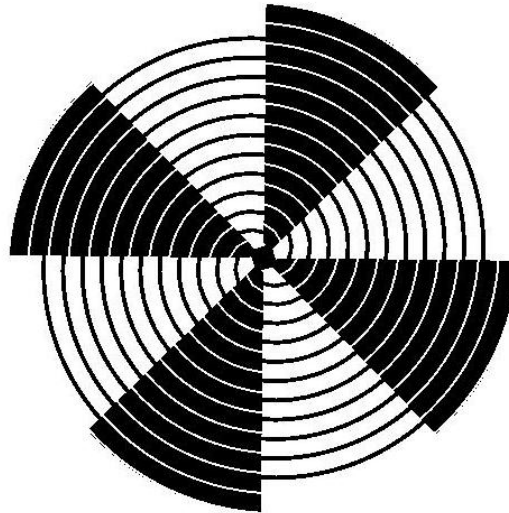


Figure 2.12: A layout of an Archimedean non-self-complementary four-arm MAW spiral with modulation ratio of 4:1 metal and a 8:1 metal to gap ratio.

The reverse mode has higher transmission line losses and consequently should be less efficient in practical implementation because it has to reflect off the outside end of the arm to return to the radiation region to radiate. This method of generating a second mode results in a significantly longer path length. Although the polarization of a MAW spiral is circular with the beamformer, the linear polarization can be achieved by combining the left and right ports through a 90° hybrid resulting in two orthogonal linear polarizations. The polarization axis of the resulting linear modes for the hybrid will rotate with the frequency at the rate of the spiral decreases with increasing frequency, thus significantly constraining the applicability of this antenna for linear polarization. Rotating linear polarization would require a frequency lookup table to determine the polarization with frequency. Sinuous antennas already have a mild version of the rotation of linear polarization condition, typically limited to 20° due to the coupling between arms. This result is one application where the sinuous is clearly more desirable than the MAW spiral.

In trying to create pure orthogonal polarizations two items are in opposition. First, the normal mode must radiate efficiently before the bandstop to avoid the higher-order mode contamination or off-

broadside axial ratio deterioration due to the reflection from the arm ends and radiation in the cross-polarized mode. In the case of a four-arm spiral, the first higher order mode is mode 5 for mode 1 operation, while the mode -3 is reflected. Mode 5 will increase pattern undulations, also known as Wobble on the Wave (WoW) while mode -3 will degrade axial ratio and possibly the impedance match. Not surprisingly, cross-polarization is more difficult to control than WoW since the MAW cannot terminate the outside to reduce reflections like a conventional spiral.

If the bandstop is not effective the pattern will have degraded WoW due to higher mode radiation. If the bandstop is ineffective it may also cause a cross-polarized term if it reflects from further along the arm producing both mode 5 and -3, (for reverse operation the modes flip and the radiation mode -1 occurs after the undesired mode 3, whereas contribution from mode -5 should be very small). With the MAW, this result typically occurs for low modulation ratios. Additionally, if the power is not reflected the efficiency of the reverse mode will be degraded.

In this section, the methods to improve WoW and polarization are discussed. Optimization of the impedance match will not be investigated, but the impedance will be evaluated on a comparative basis without implementation of a feeding geometry.

The problem in making etches with extremely high modulation ratios is the close tolerance on the gap between the wide sections and also the potential for undercutting the trace width on the narrow sections impacting the self-complementary properties of the geometry. Further investigation showed there were effective limits to the impedance not well addressed by the initial theory.

The Booker relationship based on Babinet's principle gives assurance that if the sections are complementary images (metal replaced with air and vice versa) of each other the ratio can be calculated trivially once one is known but there is a limit to the case for the ratio of metal to air. In the self-complementary case, (two arms) the result is half free space impedance, or 188.5Ω . This results in the impedance to ground of 94.2Ω when looking at the potential to ground instead of the other arm. However, if the non-complementary spiral is taken to the limit of a thin single wire the impedance is still only approximately 254Ω (less if dielectrically loaded). This was calculated from a computer simulation for a

four-arm spiral, therefore using Booker's relationship, the practical result for a band stop of the planar spiral cannot be less than 70Ω based on the ratio to the 188.5Ω self-complementary value. For the case of extremely high modulation ratios a mismatch of about 0.56 is the maximum for a single bandstop.

The Archimedean spiral has been used since the earliest days of spiral antenna engineering and though not truly frequency independent due to the growth rate being determined by arm width rather than angle it performs similarly to a frequency independent equiangular spiral. The potential differences between equiangular and Archimedean MAW spirals or the dependence of antenna performance on the type of the growth have not been researched in the open literature [55]. The un-modulated Archimedean and equiangular spiral forms in planar form are drawn in Figure 2.13 (a, b). The Archimedean spiral has a constant arm width and constant separation between arms through the entire aperture. The defining arc length equation for this antenna is still geometric growth, but because of its distribution, it will be more dispersive at lower frequencies but typically have a more symmetric pattern near cutoff.

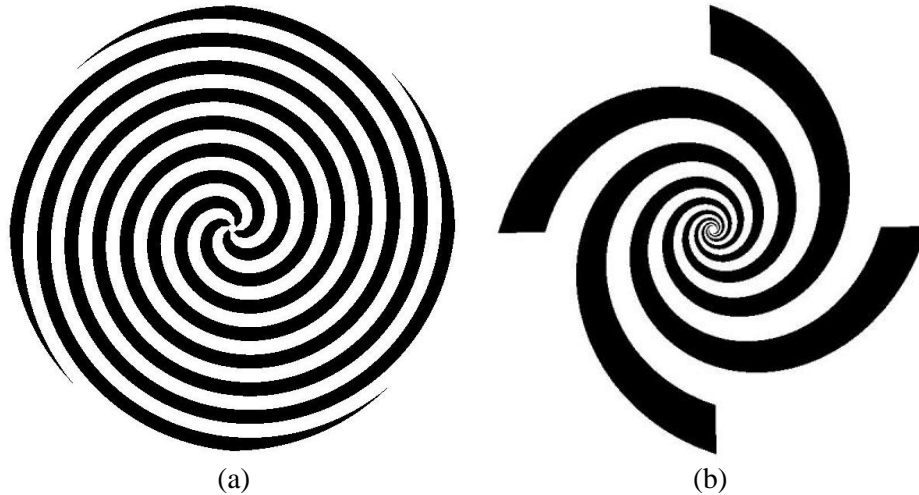


Figure 2.13: Four-arm Archimedean (a) and equiangular (b) spirals.

The spirals are shown to have two turns or wraps, but look radically different due to the difference between Equations (1) and (8). This difference, although mitigated for lower growth rates on the equiangular always puts more wraps between two large radii for the Archimedean once the arm width of the equiangular is larger than a , versus finer self-scaling structure as the center for the equiangular. Spirals as shown are in the xy plane and ϕ corresponds to the angle in cylindrical coordinates for the

normal coordinate system that shares z with the rectangular system. Equation (8) below specifies the parameters of the basis curve for the Archimedean spiral.

$$r = r_0 + a\phi \quad (8)$$

where r_0 is the starting radius, a is the growth rate, and ϕ is the progressive growth angle. The equiangular spiral has progressively increased arm width and separation between the arms as they open toward the outside. This shape can be entirely described by angles and is the basis for the frequency independent principles.

For an expansion factor approaching 1, the equiangular spiral arm width and separation between the arms, will remain nearly the same for each turn converging to the Archimedean case. Relevant parameters to evaluate the band-stop for both spirals include reverse gain, cross-polarization and WoW. Tables 2.1-3 compare the forward and reverse performance parameters for several four-arm equiangular and Archimedean MAW spirals as a function of the modulation ratio. Results listed here for the Archimedean were averaged from $2f_0$ to $5f_0$ with a logarithmic density, where f_0 denotes the cut-off frequency determined by the location of mode 1 radiating region. Frequencies below $2f_0$ were eliminated from the data set because the MAW spiral cannot radiate other modes below this frequency. Archimedean MAW spirals are computed in FEKO, while the reference data from [55] were obtained using GNEC.

Shown in Table 2.1 is the comparison between the averaged broadside gains. As seen, in the forward mode of operation both designs yield similar performance with the gain virtually unaffected by the modulation ratio. The nominal gain value is around 5.5 dBic. As the modulation ratio increases, the gain results converge to those of the forward mode. Interestingly, the Archimedean MAW spiral shows better performance, i.e., the faster convergence of the reverse gains. For modulation ratios above 4, there is virtually no difference in the averaged gains in forward and reverse modes for the Archimedean spiral, probably due to the tighter winding at large radii.

Shown in Table 2.2 is the comparison between the averaged cross-polarization levels at an elevation angle of 30° . As seen, the performance of the MAW spirals is similarly affected in both designs, which results in good performance for the modulation ratio of 8 in both designs. As the modulation ratio

increases further, the cross-polarization level in the forward mode deteriorates, while it improves for the reverse mode. This is not surprising because as the bandstop works better, mode -3 will increase while mode 5 will decrease for a mode 1 excitation.

Modulation	Equiangular Forward	Equiangular Reverse	Archimedean Forward	Archimedean Reverse
2	5.5	-1.0	5.4	2.4
4	5.6	2.1	4.9	4.3
8	6.0	4.6	5.4	5.6

Table 2.1. Average gains (dBic) of self-complementary equiangular and Archimedean MAW spirals with different modulation ratios

Modulation	Equiangular Forward	Equiangular Reverse	Archimedean Forward	Archimedean Reverse
2	-34	-9.0	-35.3	-6.3
4	-33	-12.5	-30.8	-12.8
8	-32	-16.5	-27.0	-18.0

Table 2.2. Average cross-polarization (dB) for self-complementary equiangular and Archimedean MAW spirals with different modulation ratios

Shown in Table 2.3 is the comparison between the averaged levels of pattern undulations at elevation angle of 30° , computed in terms of the WoW. As seen, the modulation ratio does not affect the forward WoW for either of the two designs. In addition, for the forward mode, the equiangular and Archimedean MAW spiral, both have the same WoW. However, the WoW is very low and consistent with the Archimedean MAW spiral, even for the small modulation ratios at high frequencies, as opposed to the observably higher values for the equiangular. This result is surprising since the equiangular spiral has a finer center structure.

The geometries chosen in the above study had the same number of turns (as shown in Figure 2.13), however, due to the different growth rates the arm-length is over twice as long for the Archimedean. The results presented in Tables 2.1-3 can be summarized as follows: the major difference is

in the reverse gain, where the Archimedean case shows significant improvement for all modulation ratios. The cross-polarization is similar. WoW of the Archimedean is slightly better, probably due to the better suppression of mode 5 over most of the operating band. It is possible that the equiangular would achieve similar results to the Archimedean MAW spiral if designed with a lower expansion factor. However, the study presented in this section is based on the same number of turns on the MAW spiral element.

Modulation	Equiangular Forward	Equiangular Reverse	Archimedean Forward	Archimedean Reverse
2	0.3	1.0	0.3	0.3
4	0.3	1.2	0.2	0.3
8	0.3	1.0	0.3	0.2

Table 2.3. Average WoW (dB) at $\theta = 30^\circ$ for equiangular and Archimedean spirals with complementary geometry with different modulation ratios

2.3.5 Arm Width Ratios that are Not Self Complementary

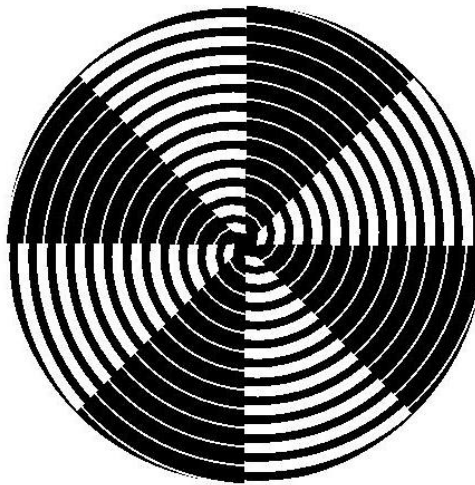


Figure 2.14: Example of non-self-complementary MAW Archimedean spiral, combining the low impedance sections from 8:1 MAW spiral and high impedance sections from 2:1 MAW spiral (of the self-complementary type)

One other way to possibly improve the MAW spiral performance is to change the average of the metal to slot away from 50% at which it is still expected to behave under Babinet's principle. By reducing the slot percentage the expected impedance could be reduced significantly closer to the 50Ω coaxial feed cluster. The research in this area showed modest improvement independent of the modulation ratio when

the average impedance was decreased. This study was not duplicated in equiangular spirals. Figure 2.14 shows the non-self-complementary structure arising from changing the base spiral from 50% metal to 77.8% prior to modulation of the spiral.

In investigating impact of MAW spiral non-complementarities on its performance, a baseline was chosen to be the Archimedean spiral, which in light of the other research makes comparisons harder. The impedance, gain and cross-polarization are of interest. For this case, the non-self-complementary structures are created in the following way. First, the ratio of the widths of the metal to the slot in the low-impedance section of the MAW spiral is set to 8:1. Then, the width of the metal sections in the high impedance regions is increased to achieve the overall modulation ratios of 2:1 and 4:1. The initial 8:1 self-complementary structure was chosen since it has the best dual-polarized performance; however it also has a significant mismatch problem.

The averaged broadside gain comparison is shown in Table 2.4. As seen, the forward gain is improved by about 0.5dB for the two studied modulation ratios. At the same time, the reverse gain has seen improvement of 2.1dB and 1.2dB for modulation ratios of 2 and 4, respectively.

Modulation	Self-Complementary Forward	Self-Complementary Reverse	Non-Self-Complementary Forward	Non-Self-Complementary Reverse
2	5.35	2.35	5.71	4.44
4	4.88	4.30	5.32	5.55

Table 2.4. Comparison of average broadside gains (dBic) between the self- and non-self-complementary Archimedean MAW spirals

Figure 2.15 shows the increasing impedance (reactive term is small relative to the resistance) on an Archimedean MAW spiral due to modulation, but some of this can be mitigated by more a non-self-complementary treatment of the feed region. Shown in Figure 2.16 is an improvement in the expected impedance ripple and its overall stability with non-self-complementary Archimedean MAW spirals. As seen, by increasing the ratio of metal to slot widths in the low-impedance region only, while maintaining the same modulation ratio, the impedance variations became almost insignificant when compared with the self-complementary four-arm spiral antenna in (b). Shown in the figure is only the forward mode of

operation. The averaged cross-polarization at 30° for the two modes of operation and self- and non-self-complementary Archimedean MAW spirals are shown in Table 2.5. As seen, both designs have very good cross-polarizations in the forward mode. In the reverse mode, the cross-polarization levels with the non-self-complementary MAW spiral are improved by about 1.3dB and 0.6dB when the modulation ratios are 2 and 4, respectively.

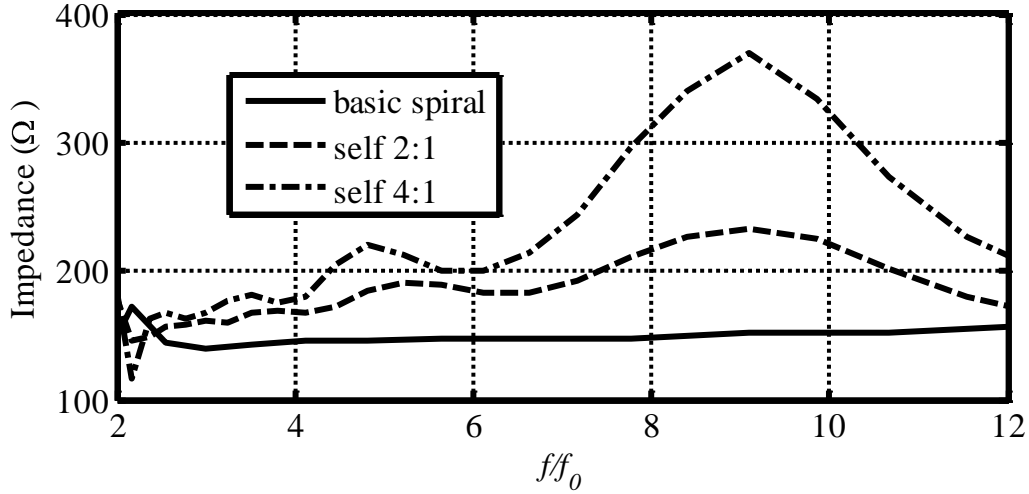


Figure 2.15: Input resistances of Archimedean self-complementary MAW spirals

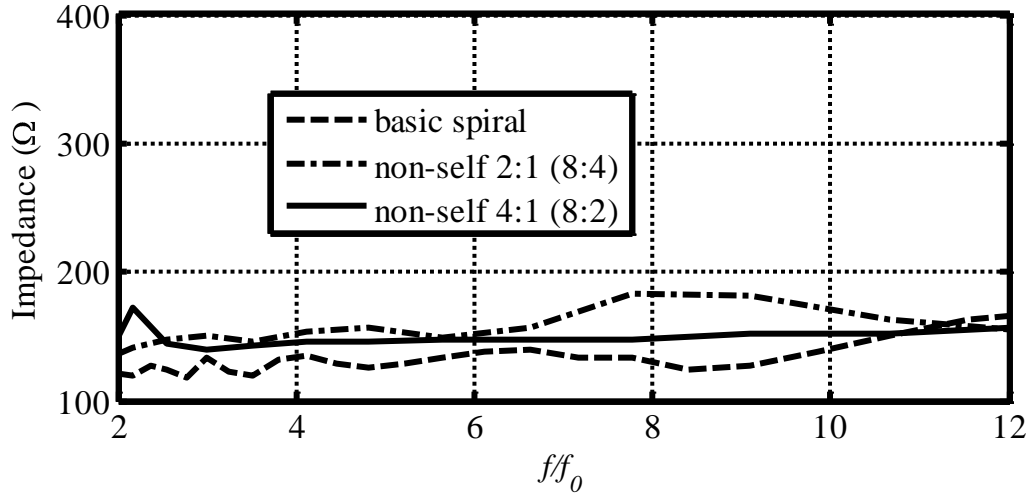


Figure 2.16: Input resistances of Archimedean non-self-complementary MAW spirals with the bandstop metal to slot width ratio of 8:1.

What the Archimedean MAW spiral exhibited here with the impedance is the interaction between the modulation sections and the feed point. Because the geometry used was starting with a high impedance near the feed point, it was quite reasonable as the impedance was lowered at the feed point launch that the overall impedance became better behaved.

The more surprising result is how well the lower average impedance made the overall performance of the Archimedean MAW spiral improve. While this result is expected to be universal, the initial significance is all these trends are in the right direction to improve the overall spiral performance by reducing the impedance from the self complementary case. Several runs on exponential MAW spirals with expansion factors of 2 did not yield as dramatic results, so the slow growth rate of the Archimedean spiral is apparently needed. Further work should be pursued in this area, as for the thesis the decision was to narrow the emphasis to spirals that had equal metal and air ratios.

Modulation	Self-Complementary Forward	Self-Complementary Reverse	Non-Self-Complementary Forward	Non-Self-Complementary Reverse
2	-35.3	-6.3	-30.4	-7.6
4	-30.8	-12.8	-29.4	-13.4

Table 2.5. Comparison of average cross-polarization (dB) between self- and non-self-complementary Archimedean MAW spirals, elevation angle is $\theta=30^\circ$

2.3.6 Bi-Layer Geometries

The bandstop performance can possibly be improved by further overlapping the adjacent arms on a printed element by putting one on the other side. This concept is a further extension of the non-self-complementary geometries. In this case, again the parametric term becomes even more awkward for modulation ratio, because the arms overlap giving rise to a nominally “negative” gap ratio. In addition, another parameter enters into the description, specifically vertical separation between the two arms. For the cases described in this section the modulation ratio was restricted to 12:1 again based on the width of metal in the high impedance section being from a parent self-complementary 8:1 geometry. For this case, 17:1 would be the highest possible ratio after which the element would short out to the opposite arm. Figure 2.17 shows the bi-layer geometry with the separation much larger than that used to see how the low impedance sections overlap in this geometry unlike the planar geometry.

The most important design parameter for a dual side (or bi-layer) MAW spiral is the separation between the arm sets due to the dielectric thickness, and the overlap, i.e. the new modulation ratio that

now allows for overlap between the low-impedance sections. The initial evaluation showed some improvements over the 8:1 baseline, single layer MAW spiral. The growth rate, feed region size / geometry, and overall diameter are kept the same for two structures and their effects will not be considered at the present time. The resistance (reactance is small) for various spaces between the 12:1 bi-layer MAW spiral is shown in Figure 2.18. As expected, the impedance is affected by the space, however, it also converges to the nominal value of 133Ω as the separation increases.

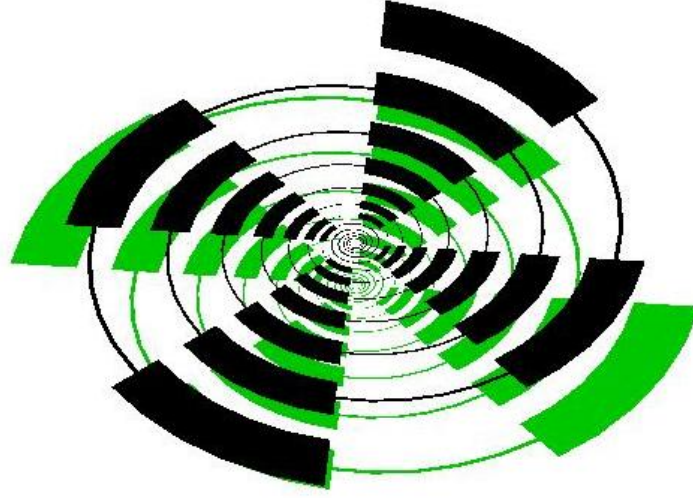


Figure 2.17: Exaggerated bi-layer equiangular spiral with 12:1 modulation and large separation to show two layers

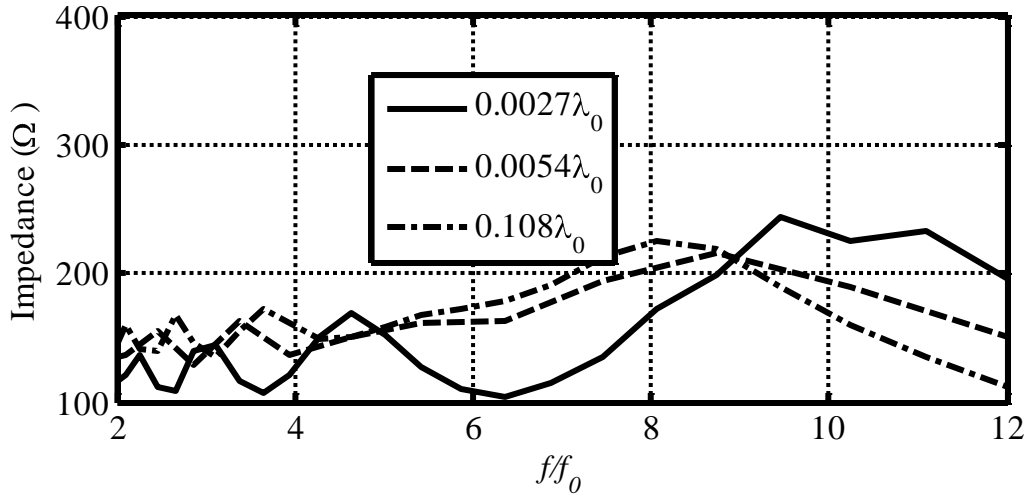


Figure 2.18: Impedance of a bi-layer equiangular spiral for different spacings between the layers.

Shown in Figures 2.19 and 2.20 are the effects of the spacing between the two sets of MAW Archimedean spiral arms to the cross-polarization at broadside ($\theta=0^\circ$) and at $\theta=30^\circ$ for the reverse mode

and modulation ratio of 12:1. As seen, the increased spacing significantly deteriorates the circular polarization quality. The dielectric was not introduced into the model for these simulations due to computational time. The dielectric will also load any built antenna significantly relative to free space predictions since significant coupling is occurring through the dielectric.

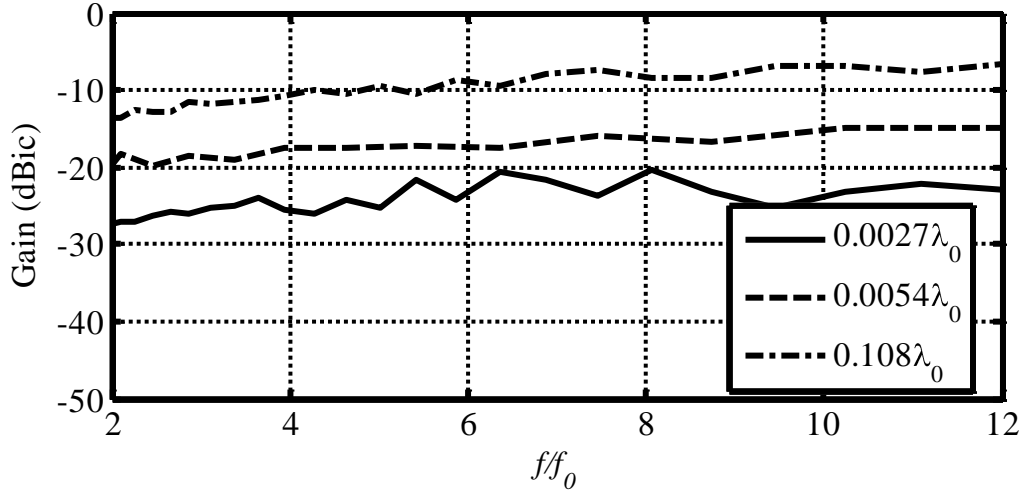


Figure 2.19: Pattern cross-polarization for antenna with 50% arm overlap and 12:1 modulation ratio at broadside with different spacings between layers

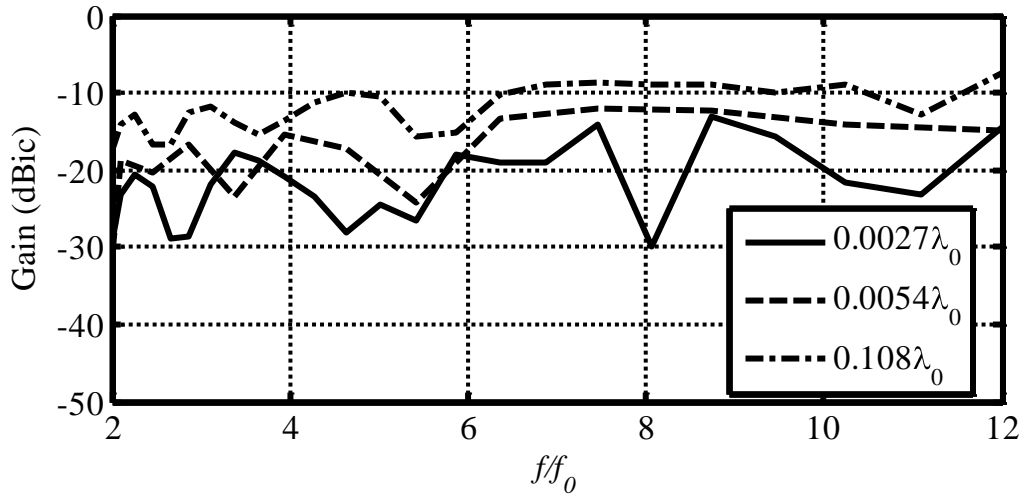


Figure 2.20: Pattern cross-polarization for antenna with 50% arm overlap and 12:1 Modulation Ratio at $\theta=30^\circ$.

The improvements associated with the ability to increase the modulation ratio by etching on both sides of the substrate are best illustrated in Figure 2.21 versus Figure 2.22. As seen, the 12:1 dual-layer MAW Archimedean spiral has improved reverse mode cross-polarized gains. The forward mode remains good at all times; however, the performance of an un-modulated spiral is about 10 dB better than any

MAW spiral.

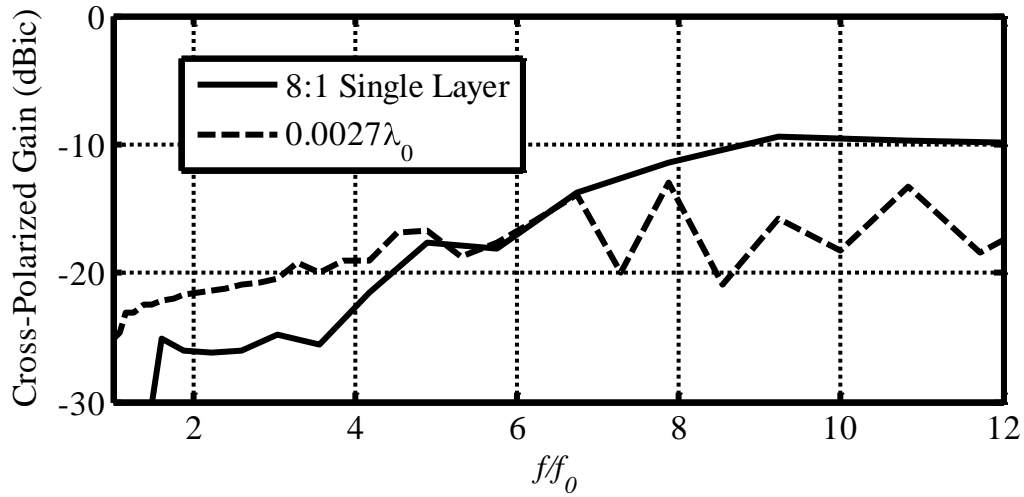


Figure 2.21: Cross-polarized gain for the reverse mode of operation for 8:1 and 12:1 modulation ratios with a single and dual layer MAW spirals at $\theta = 30^\circ$.

Shown in Figure 2.23 is a pattern comparison between the two antennas phased for operation in the reversed mode. As seen, the dual-layer design has better pattern purity for elevation angles above about 20° . The maximal cross-polarization gain for the dual layer MAW spiral is about -13 at 27° and -8.5 dBic at 40° for a single layer MAW spiral. Overall, up to about 5 dB improvement in cross-polarization is obtained with the dual-side MAW spiral. The most important phenomenon arising from the non-planar structure is the broadside cross-polarization. The planar antenna element never has a problem with broadside cross-polarization due to symmetry, but the non-planar antenna has a significant broadside cross polarization term arising from the gap between the two surfaces even though the non-planar antenna can sometimes reduce off broadside cross-pol.

The results shown in this section clearly demonstrate that the dual-layer design can be a valuable option for improving the performance of the MAW spiral. It is important to note that the numerical computations with method of moments have sometimes experienced convergence issues, particularly when the thickness of the separation layer was small. This, along with a more detailed optimization study involving the amount of overlap, dielectric constant and the thickness of the separation layer, as well as additional verifications with other tools or measurements are needed.

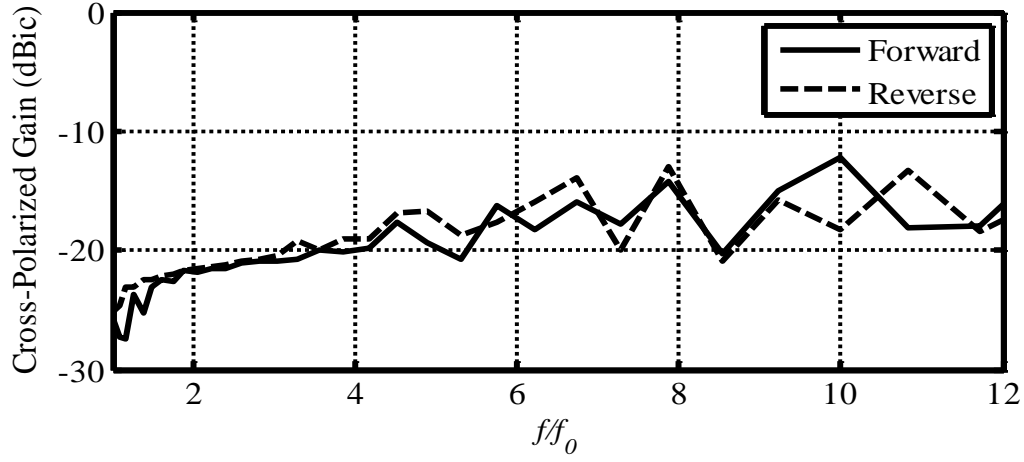


Figure 2.22: Cross-polarized gain for the dual layer MAW spiral, separation of $0.0027\lambda_0$.

Finally, the dual-layer MAW spiral configuration can be designed and fabricated with a somewhat simpler beamformer network. Specifically, to beamform modes 1 and -1 with a single layer MAW spiral, one needs to incorporate either a Butler matrix network or a combination of a 90° hybrid and broadband baluns. Instead, a simple dual-coaxial line feed structure with a single 90° hybrid can be utilized for beamforming the dual-layer MAW spiral because the inner and outer conductor can be soldered to opposite sides of the element dielectric.

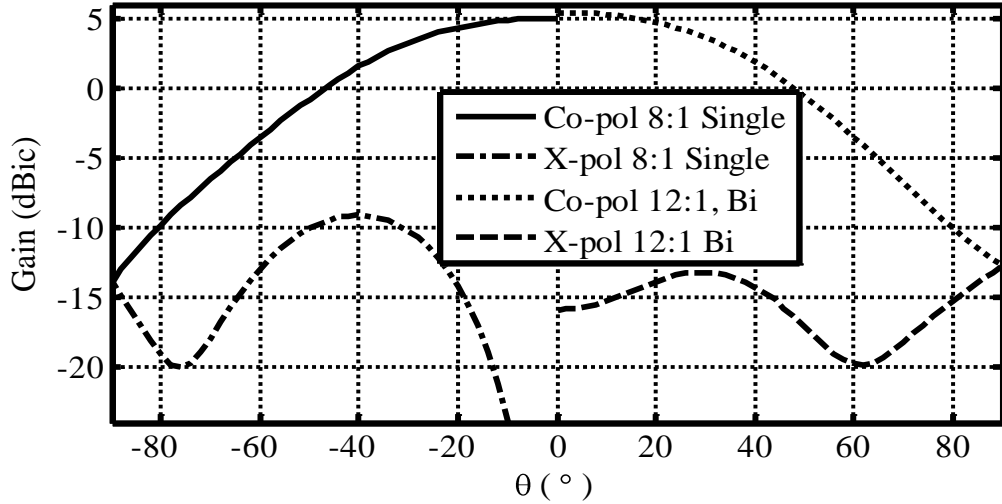


Figure 2.23: Pattern comparison of planar versus dual (bi)-layer Archimedean MAW with $0.0027\lambda_0$ spacing and 50% overlap at $f=6f_0$.

In summary, with the non-self-complementary MAW spirals, the gain, polarization and impedance can improve, indicating that band stop is more significant to overall performance than the modulation ratio itself. Based on the conclusions from this section, a way of improving the band stop is

very desirable. An improvement consisting of placing two opposite out of phase excited sets of arms on either side of the dielectric and thus achieving further reduction in the impedance of the low-impedance section was attempted mathematically. Further experimental research is needed to validate fully the above computational observations.

2.4 Design and Parametric Study

The conducted parametric study for equiangular spirals evolved around the expectation that high modulation ratio and slow growth would result in the best pattern performance of the antenna. Layouts of four different four-arm equiangular self-complementary MAW spirals are shown in Figure 2.24. In the figure, the geometry is varied by expansion factor and modulation ratio often referred to as expansion and modulation, respectively. The forward operational mode for the broadside (or z-axis) pointing out of the page of the spiral in Figure 2.24 to the observer is right-hand circularly polarized. The reverse mode corresponds to the opposite sense, thus it is left-hand circularly polarized.

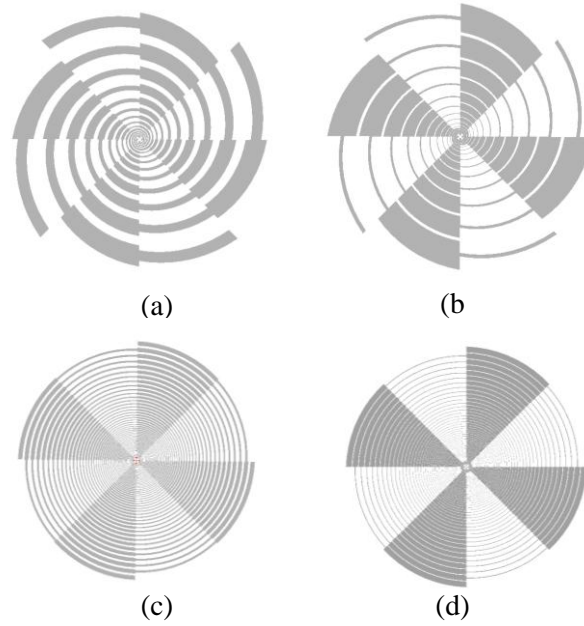


Figure 2.24: Layout of planar MAW spirals with expansion and modulation of: (a) 3 and 2, (b) 3 and 8, (c) 1.25 and 2, (d) 1.25 and 8.

2.4.1 Spiral Antenna Contribution to the MAW Spiral

Spirals, depending on the phasing of their arms generate different radiation modes. The modes generated are the standard set of harmonic functions in ϕ [56]. Limited bandwidth solutions are available

when the two modes are not collocated as in the geometry that excites both the outside and inside of the spiral [46]. Only two modes are available and the in-phase feeding would result in a differential mode if it would even radiate at all (typically impedance is very high) from the center launch geometry.

If the wrapping of the spiral with N arms ($N > 2$) is counter to the center-fed feed phasing progression with one cycle, the spiral will generate opposite polarization if the radiating circumference is smaller than $(N-1)\lambda_0$, where λ_0 is the mode 1 cutoff wavelength equal to the waveguide radiating circumference. If the spiral circumference is comparable to or greater than $(N-1)\lambda_0$, a higher-order co-polarized difference pattern will radiate. This pattern will have $(N-1)$ cycles of phase rotationally in the far-field. More importantly, the active region for the $(N-1)$ mode will be at a circumference consistent with the radiated mode. In the case of a four-arm spiral, this is mode 3. Because of this property, if a low-pass circuit element is designed and placed before the $(N-1)\lambda$ ring of radiation, λ being the signal wavelength, the bandwidth of the dual polarization spiral can be extended almost indefinitely only limited by the feed point geometry. Without a low-pass circuit, the switch between co-polarized sum and cross-polarized difference operation mode limits the useable dual polarization bandwidth of the spiral to $<(N-1)f_0$, where $f_0 = c_0/\lambda_0$, and c_0 is the speed of light.

To make the spiral both frequency independent and polarization diverse the spiral must be modified to reflect before it can efficiently radiate the undesired difference mode. To achieve this result at least two drastically different-quarter-wave impedance sections are cascaded to create reflection before the spiral's difference active region for the reverse phasing condition. For a four-arm MAW spiral, these sections will be placed at a circumference ring of 2λ . This is intentionally outside the mode 1 active region. The sum pattern will radiate at a circumference of λ and the difference pattern (consistent with reverse single cycle phasing) will be suppressed by the currents not reaching the 3λ circumference. The feed structure (beamformer) must support the two symmetric impedance modes (both positive and negative for forward and reverse operations). The MAW spiral is typically fed with a coaxial cluster mated to a beamformer which provides proper phasing between arms. As with traditional spirals, the limiting bandwidth features are the feed point radius (upper end) and antenna circumference (lower end).

2.5 Performance Measures

The performance requirements of a sensor are often more demanding than the requirements of a conventional communication antenna because of the need to address the antenna pattern as part of the transform of the received signal. Usually one can define a communication antenna by mismatch, gain, polarization and beamwidth. On rare occasions, first sidelobes matter because of the potential to try to make a link on the sidelobe rather than the mainbeam in particular if the sidelobe is too high it can cause links to adjacent satellites to be contaminated, reduce the polarization reuse of an antenna or its ability to be used in other more sophisticated applications such as SAR.

In a sensor's most sophisticated implementation even the time response is significant because it can cause dispersion of signals that have extreme bandwidth. For most signals where the bandwidth is small ($<5\%$) resulting in an almost constant group velocity. This term can be neglected for an FI sensor and then the response as a function of angle and polarization become critical. Investigation into wideband signals is not a goal of this thesis but from Chapter II it was shown that the dispersion of the MAW spiral was in the nsec^2/m , range. These requirements quickly becomes having the pattern as symmetric as possible to make it easy to array the antenna for enhanced resolution of the received signal with minimal dispersion. Having an antenna that is blind to a particular angle, polarization or frequency will significantly degrade the overall effectiveness of the device. Also, having patterns that are not simply related to each other by either being identical or having a single value map from the one pattern to the other is very important. In this section, we will define some of these less commonly used figures of merit and explain their significance to expressing performance of the antenna as a sensor.

That is not to say gain is not an important performance parameter of any MAW design, but the best gain for a symmetric pattern is already controlled by attempts to reduce cross-polarization and pattern ripple that are discussed below. The gain is still the first test that the design has any promise; if the forward and reverse gain are not similar then the bandstops are not performing well in the design.

2.5.1 Polarization

For polarization of a sensor it is much more important to be consistent than good, although the

two usually happen together. In particular if one is comparing the response of an antenna to a signal received at two different angles, the first requirement is they have the same magnitude response at least if elevation (θ) is constant. This constant response requirement ensures that the sensor has the same sensitivity at all azimuth (ϕ) angles while allowing the designer to modify the pattern in θ to improve sensitivity in the desired region of coverage. If the sensor is dual polarized, then being able to determine the polarization of the signal should be straightforward, but works best if the patterns are orthogonal at the angle the signal is detected. The best way to evaluate this behavior is by determining the dot product of the two patterns, if the patterns are perfectly orthogonal the result is zero at all angles of coverage. A non-zero result directly correlates to how large the error on polarization measurement will be if not compensated. However, compensation can only occur if the signal direction is known which would require the overall instrument to be much more complicated and introduce another potential error of knowledge of the signal direction. Thus signal orthogonality is an important term when defining the multi-polarized sensor's performance.

2.5.2 Beamformer Modal Purity

The beamformer also limits the performance of the sensor; however, this thesis does not examine its effects in greater detail. From the standpoint of sensor performance, the beamformer is responsible for removing all modes that are close to the desired mode and are not a multiple of the arm count of the spiral. In other words, for a four-arm spiral a beamformer can output mode 1 to a discrete port while filtering modes 0, 2 and 3 into different ports or loads. However, if the mode is 5, -3 or -7 the four-arm beamformer cannot distinguish these modes from mode 1, only the antenna element can remove those responses. For the definition of the performance, it is best represented as the rejection of other modes. The typical efficiency this is done with is about 20 dB or 1 percent contamination. For the design evaluations done here, the control goal was to reduce any pattern contamination to the level where this property was the limit on performance. This value still corresponds to a pattern ripple of 1.7 dB peak to peak in ϕ if the two modes have the same normalized power at the angle of interest. Modal purity is calculated by the modal split of the beamformer using a Fast Fourier Transform (FFT) to sort the beamformer into

symmetric orthogonal responses. The response using this approach determines for a given input port how much power is delivered in the defined mode. For the four-arm case, the single arm response has a 6 dB insertion loss from the power division on top of whatever losses due to ohmic and modal. If the result of the four arms is processed as described above with the FFT, the results show the performance for a component beamformer with internal (ohmic and mismatch) loss increasing with frequency from 1 to 5 dB over a 20:1 bandwidth and a minimum modal purity of 10 dB. The results can be demonstrated for each mode. In this case, the reflection of all the components was optimized for 50 Ω by the manufacturer, but a transformer could be designed to recover the mismatch loss of 0.5 dB between the beamformer and the antenna, because for the four-arm spiral the input impedance is approximately 100 Ω on each arm in isolation. The component beamformers have high isolation port to port (rarely would one expect a hybrid to have 6 dB coupling between the two ports by design), building one to have the same coupled behavior as the spiral would be difficult, especially if more than one mode was desired.

2.5.3 Pattern Purity

Pattern purity begins with symmetry of the pattern if spun around the broadside. This term is frequently referred to as WoW because when plotted it has typically multiple ripples but is periodic in ϕ . The period of these terms usually are an indication of the source of pattern contamination. If the pattern has a single cycle, the source is usually the beamformer. Two cycles will usually arise when the antenna is near cutoff and the single arm pattern is more like a dipole. If the period is the same as the number of arms, then the dominant polarization of the ripple quickly defines if it is a reflection (cross) or higher order (co) due to poor radiation. Both of these phenomena are negligible below the cutoff of the respective mode, as in reverse operation of a four-arm MAW, modes would be 3 and -5 respectively and could only radiate efficiently if the circumference was >3 wavelengths.

2.5.4 Termination

The termination of conventional spirals is usually done with either a taper as the spiral crosses the edge aperture or the arm is terminated into a series of resistive loads that provide a good match even far below the antenna's cutoff. Commercial antennas clearly use both the short and open geometries as

observed in their literature, showing elements done both ways.

Terminating a MAW spiral is problematic because the reflection is needed for reverse operation. However, the reflection causes an impedance spike in operation when the reflected wave interferes with the arm termination destructively. This situation is narrowband, but as shown in the results below it can be tuned to reduce the magnitude of the ringing. The MAW spiral should not be terminated with a resistive load since the dual polarization operation is then compromised below $2f_0$. Investigation of the length of the terminating section indicates the reverse gain drop-out at about $f/f_0=2$ can be reduced if the antenna ends in a low-impedance section. Figure 2.25 and 2.26 show where the last section was varied from 45° (an eighth rotation or $\lambda/4$ at $2f_0$) to a full low-impedance section. As seen, when the MAW spiral termination became a low impedance transmission line the decrease in gain was significantly reduced.

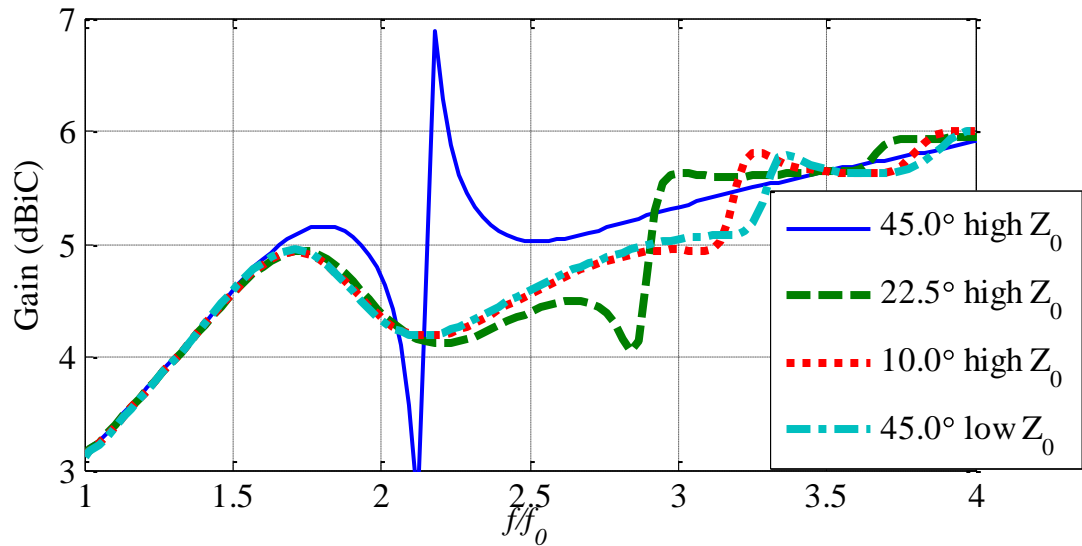


Figure 2.25: Simulated reverse operation broadside gain near cutoff for different termination lengths in the final bandstop with either low or high Z_0 .

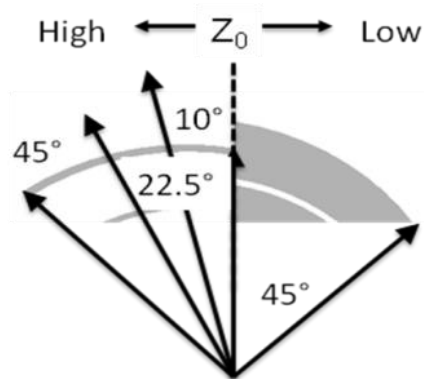


Figure 2.26: MAW spiral termination geometry with the different cut locations for Figure 2.25.

Reverse gain changes significantly with the terminating section due to the interaction between the bandstop and the open end of the MAW spiral. Once the reflection of the bandstop is shifted off resonance, the smoothness of the gain improves until the section becomes low impedance. At this point, the gain gradually degrades back to the high impedance resonance. The phasing between the bandstop region and the open at the end of the MAW spiral will always vary some because of the difference in delay. Tuning for the removal of the resonance is the last step after choosing an expansion factor reasonable for achieving low loss, an accurate etch, and acceptable pattern performance. Note, the better the bandstop reflects the current, the more the termination reflection is reduced. Realistically, from the discussion on bandstops alone from above, the best suppression of the reflection that can be hoped for is perhaps 3 dB so making sure the antenna radiates mode 1 efficiently is more important in the designs investigated. The reducing of the expansion factor should help by reducing currents past the radiation region while introducing more separation between the bandstop and the radiation region.

2.5.5 Ripple from Modulation

The antenna performance is dependent on a design of four operational regions: balanced feed line, active region, bandstop section and termination. Typically, the feed lines should be optimized for accepting input to a 50Ω unbalanced coaxial line. However, more complex feed line geometries could be utilized such as the Dyson infinite balun [57] or a non-coaxial transmission line [58]. For mode 1 operation the ratio of metal to non-metal should approach 10:1 for the feed line region. This feed line section needs to be a significant portion of the longest wavelength of operation ($1/8 \lambda_0$) to improve the match across the operation band. Getting this feed line length inside a circumference of $3/10\lambda_0$ for 10:1 bandwidth (modulation dimension to eliminate mode 3 operation) requires a low expansion factor. In the active region, the expansion factor needs to be low to reduce the gain ripple. Figure 2.27 shows the decrease from 1.5 dB to 0.75 dB in gain ripple as the expansion factor decreases.

The bandstop region needs to have minimal reflection when it is part of the active region at lower operating frequencies. When used as the bandstop section, the rejection should be a perfect open or short to prevent further propagation of a traveling wave and undesired radiation of other modes. Even a good

rejection leads to increased WoW. WoW and high cross-polarization where the higher order modes occur both can have significant power. In addition, WoW is an important parameter for direction finding systems accuracy in elevation and its reduction is critical for improving the accuracy thereof.

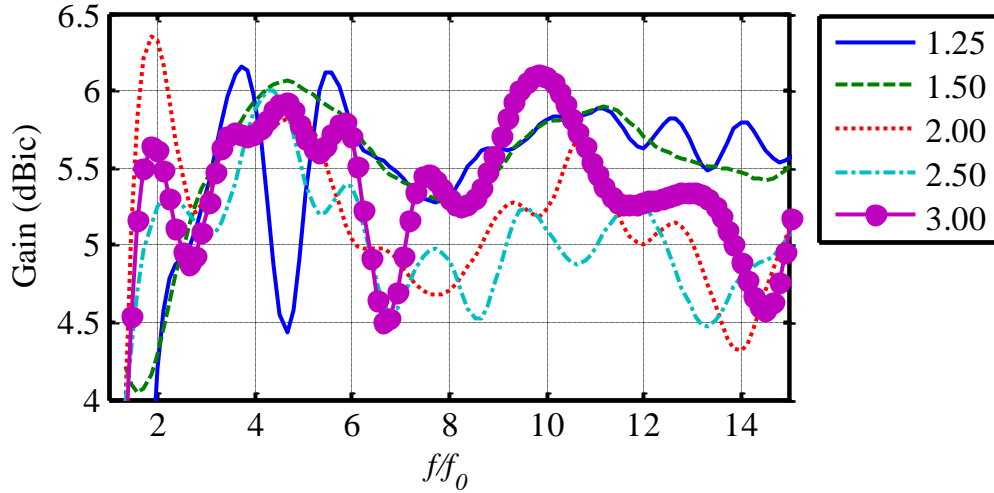


Figure 2.27: Simulated broadside gain for different expansion factors. MAW spiral is terminated by the low-impedance termination (45° low Z_0 in Figure 2.26), and its modulation is set at 8.

The selected MAW spiral designs are expected to have a reasonable match to 100Ω when using a matching transmission line section at the feed point as described in the previous section. Although the coax is 50Ω , the antenna impedance is based on the mode, whereas the coax impedance is the arm referenced to ground. Since the MAW spiral is self-complementary beyond the feed point, constant real impedance should be obtained. This is shown in Figure 2.28 for expansion factor 2.5 and different modulation ratios. The model predicts impedance mostly varying between 100 and 150Ω . Below twice the cutoff frequency, the reflection of the termination causes excessive ringing making this design an unlikely candidate to miniaturize since it only has constant impedance above $2f_0$. The impedance ripple increases with higher modulation and the period decreases slowly relative to frequency.

Other methods to improve the match to conventional coax through the feed point are possible but not investigated as part of this study. Reactance increases due to the reflection at the end of the transmission line. The effects of expansion factor and modulation ratio on dual-polarized performance are demonstrated next. These results are obtained by averaging computed performance parameters above $2f_0$ to avoid variation in the termination effects for different geometries. Dielectric effects are not considered

for design tradeoffs, however, the presented results are still valid for antennas built on thin low-permittivity substrates.

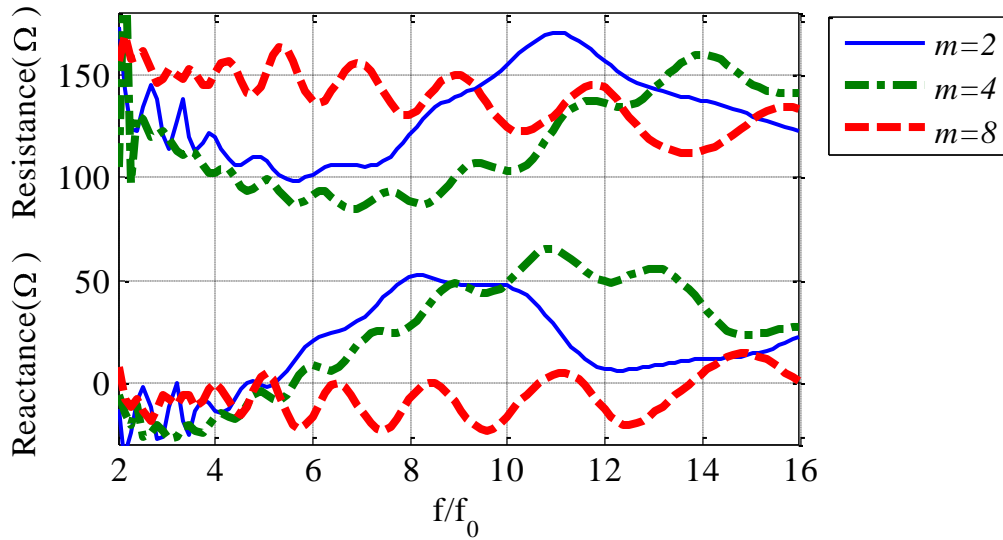


Figure 2.28: Simulated results for antenna input resistance (top) and reactance (bottom) variation over frequency. Modulation (m) of 8 has a quarter turn matching section, modulations of 2 and 4 have full turn transmission line launches.

2.5.5 Current Behavior

In understanding how the MAW spiral creates dual polarization, several phenomena need to be better described. First and most importantly is the significance of coupling between arms and its effect on performance of any spiral. While the spiral is feed by a multi-conductor transmission line, the strongest coupling term is at the feed point, especially if it is not distributed over a significant portion of a wavelength. The dominant coupling arises from the transition from a coaxial (unbalanced) to a multi-conductor (balanced) transmission line. Matching the impedance at the feed point only provides an improvement in match for one mode and its complement, and does little to reduce overall arm coupling that is caused by the different modes. The structure has a defined impedance for each mode from geometry that requires coupling to excite the transmission line structure [16].

The most important result of this effect is that for design considerations coupling beyond the feed point can usually be neglected. Figure 2.29 shows single arm data with and without feed point coupling for the conventional four-arm MAW spiral from Figure 2.24 (c). The feed point coupling was removed from the full wave response by taking advantage of a constant phase with frequency that arises from

feedpoint coupling since it has no delay and a FI response. If the remaining coupling was from the transmission line or spiral, it would show a significant time delay manifested as a rapidly varying phase.

Figure 2.29 establishes that the single arm performance dominates the overall performance on the MAW spiral. It is good to understand what is unique about the single arm pattern of the MAW spiral. In particular, knowledge of the single arm performance will tell you which modes are available, thus allowing you to determine how best to control them. If a single arm of the MAW spiral is measured, the polarization is linear as in Figure 2.30 as shown in the polarization G_θ and G_ϕ where the polarization rotates with the arm but since it is broadside must flip polarizations. A conventional spiral, either equiangular or Archimedean, will be circularly polarized on each arm because the beamforming of the arms only controls pattern not polarization. Because the MAW spiral arm winds in shape of a spiral, the single arm beam peak also spirals with the changing resonant circumference of the antenna over frequency, as shown in Fig 2.31. The single arm beam does not peak at broadside (except for $f < 2f_0$), because the pattern is a combination of all modes that radiate efficiently. Thus the beam peaks at 20° due to the $\mathbf{M} = 2$ component. This behavior is consistent with the equiangular single arm spiral for pointing, but with a sinuous single arm for polarization. A single arm of a spiral is circularly polarized above cutoff and the peak of a sinuous single arm will only wobble within some small range that is a subset of the angle swept out by the single arm. By contrast, the MAW spiral combines beam rotation and orthogonal polarization between adjacent arms and generates all three lowest modes.

In Figure 2.30, the components of the single arm are compared to the combined four-arm antenna. The G_{maw} trace shows the broadside performance of the antenna through a lossless four port beamformer. If a single arm is measured with matched polarization, and the power is no longer distributed between the four arms, the broadside directivity drops by 3 dB, due to half the power being lost to the power split between mode 1 and -1. This loss is not in gain of mode1 because it is isolated from mode -1, but in single arm gain, if the arm radiated more modes efficiently the gain would drop even further as without a beamformer the single arm has no way to filter the gain by mode.

If the field of a single arm is separated into polarizations as shown in the G_θ and G_ϕ traces of

Figure 2.30, the polarization on broadside rotates with each turn of the MAW spiral arm. Off axis, the structure of the single arm polarization becomes more complicated by $M = 2$ rotating at a different rate than $M = 1$, causing the matched polarization gain to spread to more than 3 dB at a fixed θ for a single arm. This is unlike the single value observed at broadside and is why a beamformer is required to remove other modes from the single arm response and enforce symmetry.

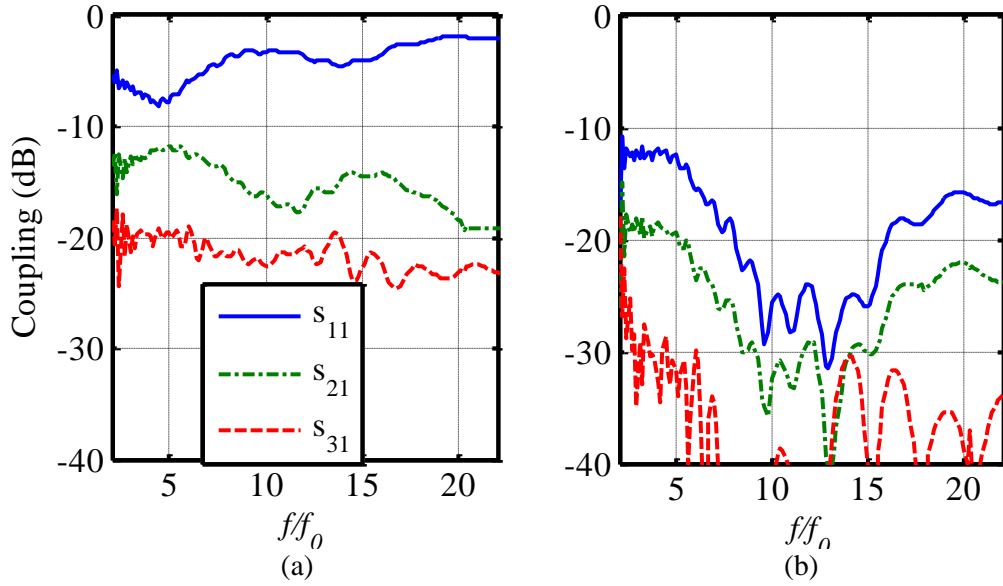


Figure 2.29: Coupling for arms before (a) and after (b) the feed point term is removed.

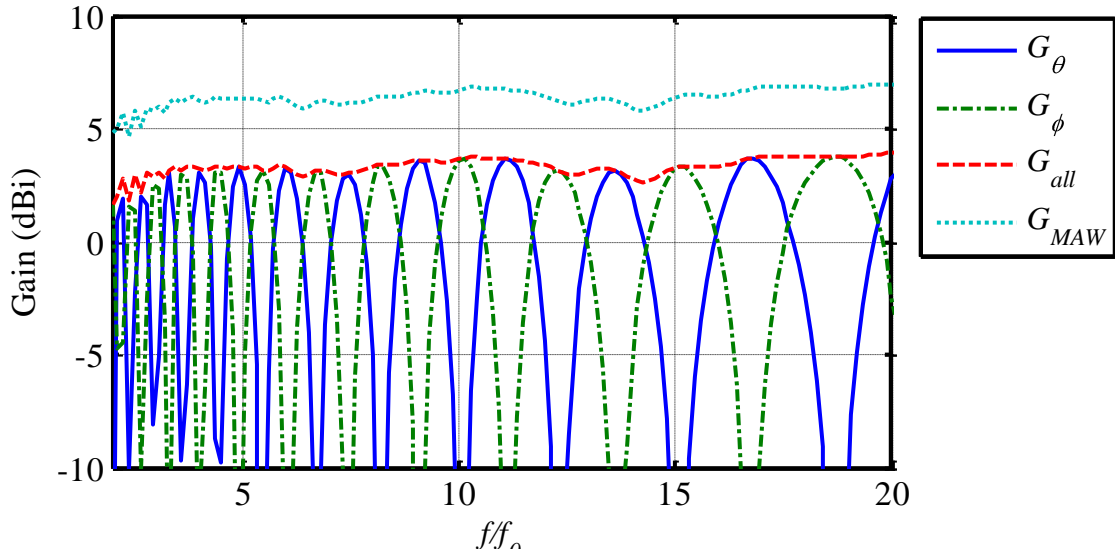


Figure 2.30: Performance of a single arm of a four-arm MAW spiral compared to four-arm performance showing the polarization and beamforming constituents on broadside.

The primary conclusion is that for the MAW spiral to work best the transition has to be improved

at the feed point. Some improvement in the reverse operation is provided by coupling, because it is strongest on adjacent arms and reaches the radiation region in phase with the nominal arm improving the overall reflection efficiency significantly. This behavior is seen in the antennas with a modulation of 4, which would be only expected to suppress the cross-polarization term 6 dB but provides performance closer to 20 dB if the growth is low enough which also improves the phasing on the coupling coherence with the radiating arm.

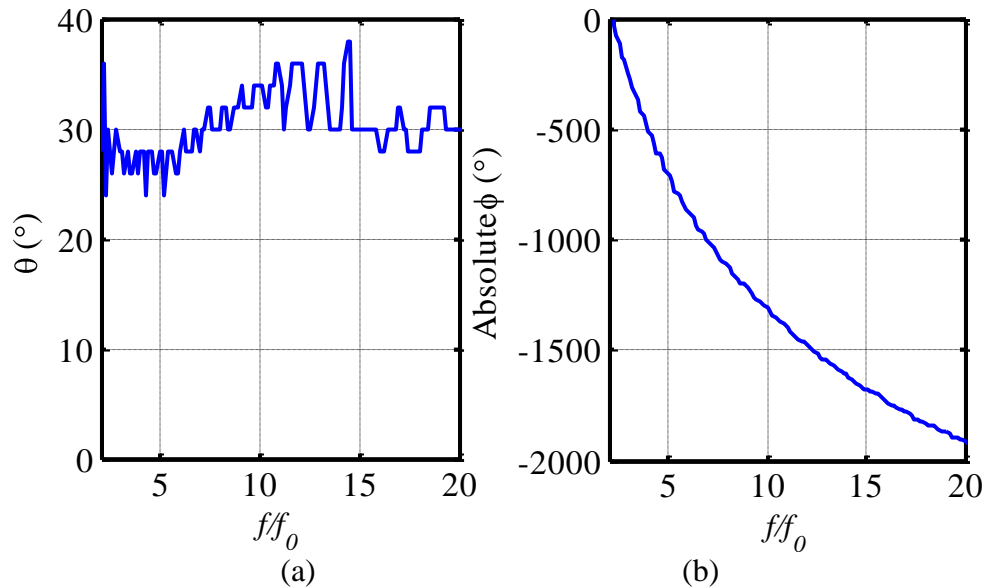


Figure 2.31: Single arm beam peak location, (a) off broadside point, (b) frequency tracking rotation.

2.6 Antenna Performance from Parametric Study

The quality of dual circularly polarized operation for mode ± 1 is first evaluated using broadside gain. Ideally, a MAW spiral will have the same gain in both polarizations. As Table 2.6 shows, the expansion factor must be low for this limit to be approached, unless a high modulation is used. However, a high modulation increases mismatch loss. While the improvement in forward gain for smaller expansion factors is less than 0.5 dB (reaching a maximum of 5.5 dBic), the reverse operation gain exceeds 5 dBic if the modulation is ≥ 8 or the expansion factor is less than 1.5 and modulation is greater than 4. The average values are obtained as the arithmetic mean of a specific parameter (G, WoW, X) for all computed frequency points above $2f_0$. Data points below $2f_0$ are excluded to eliminate the effects of imperfect termination and thus represent the antenna performance only over its frequency independent bandwidth.

Polarization purity is investigated next. In a model, broadside cross-polarization is always suppressed unless imposing beamformer imbalances. Thus, the cross-polarization performance investigation is off-axis at 30° and 60°. The polarization purity degrades when off-axis angle increases and the reverse mode operation is always substantially worse than the forward mode (see Tables 2.7 and 2.8). Note that the axial ratio and cross-polarization (X in dB) are related as

$$AR \text{ [dB]} = 20 \log \frac{10^{-X/20} + 1}{10^{-X/20} - 1} \quad (9)$$

Thus, the average axial ratio at 30° in the reverse mode of operation for a MAW spiral with expansion factor and modulation ratio of 1.5 and 4, respectively, is 2.2dB (-18 dB cross-polarization). At 60°, the axial ratio deteriorates to about 5.7dB (-10 dB cross-polarization). Tables 2.7 and 2.8 show the data for typical cross-polarization of the MAW spiral with four arms at 30° and 60°, respectively.

		Expansion Factor									
		1.25		1.50		2.00		2.50		3.00	
		G_f	G_r	G_f	G_r	G_f	G_r	G_f	G_r	G_f	G_r
Modulation	2	5.5	4.9	5.5	3.7	5.4	1.6	5.4	0.3	5.3	1.2
	4	5.5	5.4	5.5	5.4	5.4	4.7	5.4	4.5	5.2	4.3
	8	5.3	5.3	5.4	5.5	5.3	5.2	5.2	5.0	5.1	5.4

Table 2.6: Computed average broadside gain (dBic) for different modulation and expansion factors (no ohmic losses included). G_f is gain in forward operation and G_r is gain in reverse operation.

		Expansion Factor									
		1.25		1.50		2.00		2.50		3.00	
		X_f	X_r	X_f	X_r	X_f	X_r	X_f	X_r	X_f	X_r
Modulation	2	33	12	32	6	31	3	30	1	29	2
	4	31	31	32	18	30	14	30	13	28	10
	8	31	30	30	27	28	22	27	19	26	18

Table 2.7: Computed average relative cross-polarization at $\theta = 30^\circ$. X_f is cross-polarization in forward operation and X_r is cross-polarization in reverse operation.

Higher modulation improves the cross-polarization under all conditions, with the reverse operation approaching forward for an expansion factor of 1.25. Note that this topology corresponds to 16 wraps and thus increased internal loss and tighter tolerances. In accomplishing this cross-polarization reduction, only slight performance degradation is predicted in forward operation. A slow expansion improves the cross-polarization by 5 dB over an expansion of 3. The recommendation is to use low expansion factors to achieve similar cross-polarization for both modes.

		Expansion Factor									
		1.25		1.50		2.00		2.50		3.00	
		X_f	X_r	X_f	X_r	X_f	X_r	X_f	X_r	X_f	X_r
Modulation	2	20	5	20	-1	19	-4	19	-5	19	-4
	4	19	20	19	10	19	6	19	6	18	3
	8	19	19	19	17	18	14	17	11	17	9

Table 2.8: Computed average relative cross-polarization at $\theta = 60^\circ$ (negative values exceed nominal co-polarization). X_f is cross-polarization in forward operation and X_r is cross-polarization in reverse operation.

Note that for WoW the performance approaches a minimum at 1.5 regardless of modulation and even to some degree polarization. Additionally, the WoW increases with angle due to the increased power in higher order modes as well as the decreased gain of the mode 1, which is down by almost 8 dB at 60° as opposed to 1.5 dB for the 30° . Even without increase in the power in the modes, the WoW would increase by for 0.1 to 0.21 dB. Given that mode 5 and -5 will peak around 60° the additional doubling of the ripple would be expected. In addition to the higher order modes, the MAW spiral or any planar spiral will have increasing WoW based at 60° because the element loses polarization symmetry of the currents as it dips further off broadside. This phenomenon also results in increasing cross-polarization because the currents are confined to the plane and to achieve circular polarization the θ , ϕ components must still be equal like of the θ , ϕ components on broadside. Increasing the number of arms will reduce the higher modes, and to some extent the polarization symmetry.

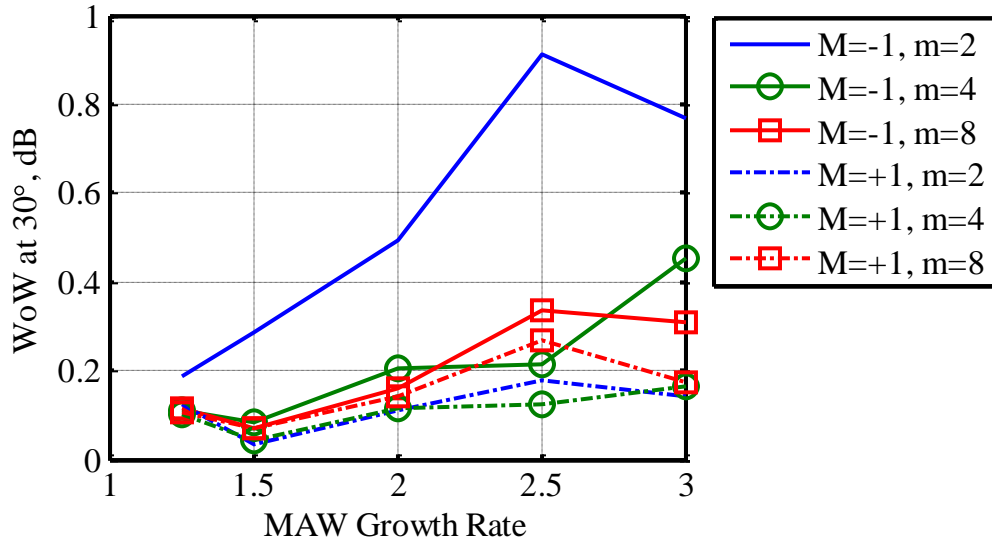


Figure 2.32: Computed forward (mode 1) and reverse (mode -1) average WoW at $\theta = 30^\circ$ for different MAW spiral expansion factors and modulation ratios.

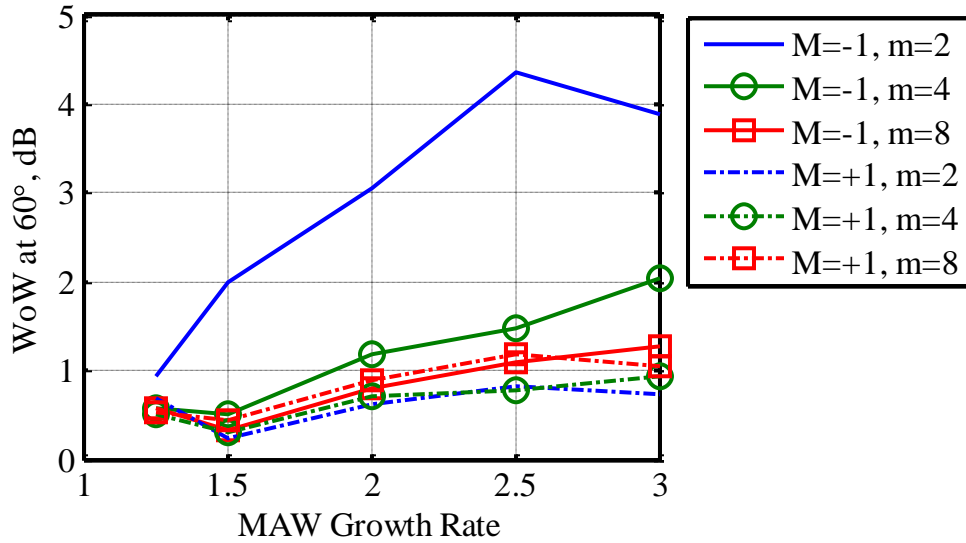


Figure 2.33: Computed forward (mode 1) and reverse (mode -1) average WoW at $\theta = 60^\circ$ for different MAW spiral expansion factors and modulation ratios.

The final parameter investigated is the pattern symmetry expressed as WoW. WoW arises from modes radiated by the currents flowing in the same direction as the desired mode. For a four-arm MAW spiral this is predominately mode 5. Figures 2.32 and 2.33 show average WoW at 30° and 60° for various design expansion factors and modulations. As seen, WoW converges faster than the cross-polarization performance, but still requires a modulation of 4 or better to achieve wide-angle beam symmetry for both modes of operation.

2.7 Measurements

A test article having two modifications of a traditional MAW spiral given in the patent [7] was fabricated and is shown in Figure 2.34. The modifications were moving the modulation outside the active region at the highest desired operational frequency and increasing metal to slot ratio in the center to lower nominal antenna impedance. A 13 cm diameter antenna was printed on a 0.5 mm thick Rogers 6002 dielectric with permeability of 2.94 and loss tangent of 0.0012 at 10 GHz. Material properties were verified using a GDK open cavity dielectrometer, accuracy < 0.05 [59]. An expansion factor of 3 was used to allow an accurate etching of the 4:1 bandstop. The termination transmission line sections were matched to a full eighth rotation (45° of Figure 2.26), but high impedance of the termination assured a null at $2f_0$. A 2.18 mm (0.086") coax feed cluster was used to feed the antenna. The chosen geometry does not have the best performance among the evaluated antennas, however, it enables radiation of undesired modes ± 3 , ± 5 , -7 and 9 to a level that the far-field pattern would have significant contamination and modeling validation becomes more thorough.



Figure 2.34: Photograph of a fabricated MAW spiral with expansion of 3, modulation of 4 and non-complementary center region enlarged by 4X.

Measurements are processed within the limits of the phase matching of the coaxial cluster feed. Three methods are used to predict the composite pattern from a single arm measurement. The first is to measure each arm independently and combine the results with an ideal beamformer. This approach is prone to fabrication uncertainty due to phase matching and connectorization. This uncertainty can be reduced by inspection of measurements since each arm should match the response of the other arms except for a physical rotation of the arm by 90° multiples in ϕ . One advantage of this processing method is

that the modes are still available that a perfect beamformer would terminate to a load (so that if mode 1 is excited, the data will still have any pattern information from modes in 2,3 and 4).

The second method uses a single arm measurement and post processes data by rotating a particular arm and synthesizing the overall response by summing all properly clocked arm rotations. This processing approach results in an N fold symmetric total data set. This method reduces fabrication errors since all arms are assumed identical. Any asymmetry or misalignment of the antenna will however increase pattern errors from prediction. Determining the misalignment is more difficult from measurement because components of patterns due to multiple modes cannot be isolated from alignment. Alignment errors also increase adjacent modes due to phasing modulation of the alignment error.

The last approach uses measured single arm data to calculate the mode spectrum by Fourier transform. While this method easily determines the contamination arising from undesired modes, it filters the components that cause pattern WoW and axial ratio. Special care must be exercised to pass the modes that the ideal beamformer would also pass. When done correctly all methods should provide similar results for all modes of operation if the antenna is well built and aligned.

Measured results for all three methods are shown in Figure 2.35. They are denoted as $\Sigma E_n E_1(\text{rotate})$, and $\int E_1(\phi) e^{M\phi}$, for the first, second, and third method, respectively. Off-axis gain at $\theta=30^\circ$ was used since the rotation of arms and Fourier transform are equivalent at $\theta=0^\circ$. There is a strong consistency between different measurement processing methods, which implies the errors in antenna fabrication and range alignment are small. In addition, the modal contamination is small for the selected angle ($\theta=30^\circ$) since only a slight performance change was observed between the first and third method.

Figure 2.36 shows that the WoW is affected as the effective electrical thickness of the dielectric increases past $\lambda/5$ which occurs for this specific article at $f=10f_0$. Below this frequency, the difference between the method of moments computations using multi-level (MLGF) and free-space (MoM) Green functions are relatively small relative to other unknowns (proving our premise of design tradeoffs not requiring dielectric). This result implies the parametric evaluations done on the free space design apply if the dielectric is kept thin and low-loss. Note that the adverse effects of dielectric loading require the use

of thin, low permittivity substrates. The model prediction is consistent with the measured results as shown in Figure 2.36 where the pattern of only one measured arm is used. The inclusion of additional arms in the final pattern prediction increases the overall variations due to both fabrication and range measurement.

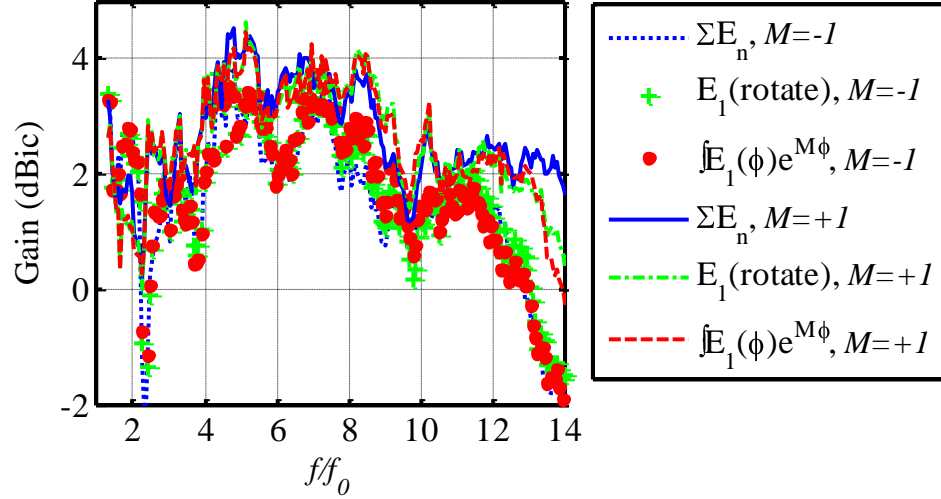


Figure 2.35: Measured gain for the forward (mode 1) and reverse (mode -1) by the ideal beamformer methods at $\theta=30^\circ$, $\phi=0^\circ$.

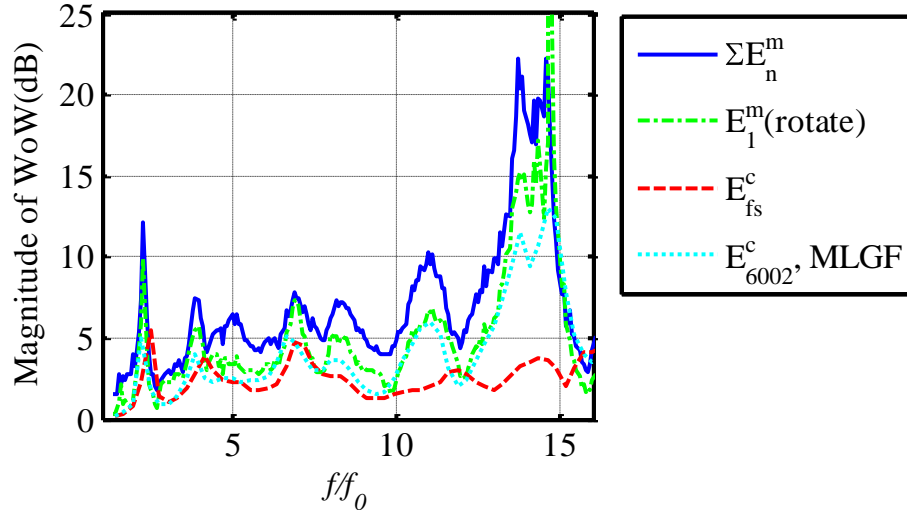


Figure 2.36: Dielectric loading effects on WoW at $\theta = 60^\circ$ using measurements and simulations denoted in superscript as ‘m’ and ‘c’, respectively. Subscripts denote: ‘n’ for all n arms excited, ‘1’ for one arm excited, ‘fs’ for free-standing MAW computed using free-space Greens function, and ‘6002’ for Rogers dielectric 6002 computed using MLGF.

The degradation in WoW above $f=12f_0$ is expected due to the modification in the feed region. Therefore, without a full bandstop, mode 3 is generated by the same beamformer as mode -1. Thus mode 3 can radiate providing a large WoW at 60° while causing a much smaller increase at 30° since mode 3 peaks at 45° while mode -1 rolls off at least 5 dB at 60° . Note that modes ± 2 are rejected by the

beamformer.

As shown in Figure 2.37, the full-wave model predicts negligible WoW for the forward operation below $7f_0$ while the measurements show a highly varying WoW with the average value about 0.25dB higher than simulations (the additional WoW would correspond to -31 dB for chamber reflections). It is likely that the chamber multipath is the cause for this discrepancy, but otherwise the correlation is excellent. Results are similar at larger angles as shown in Figure 2.38.

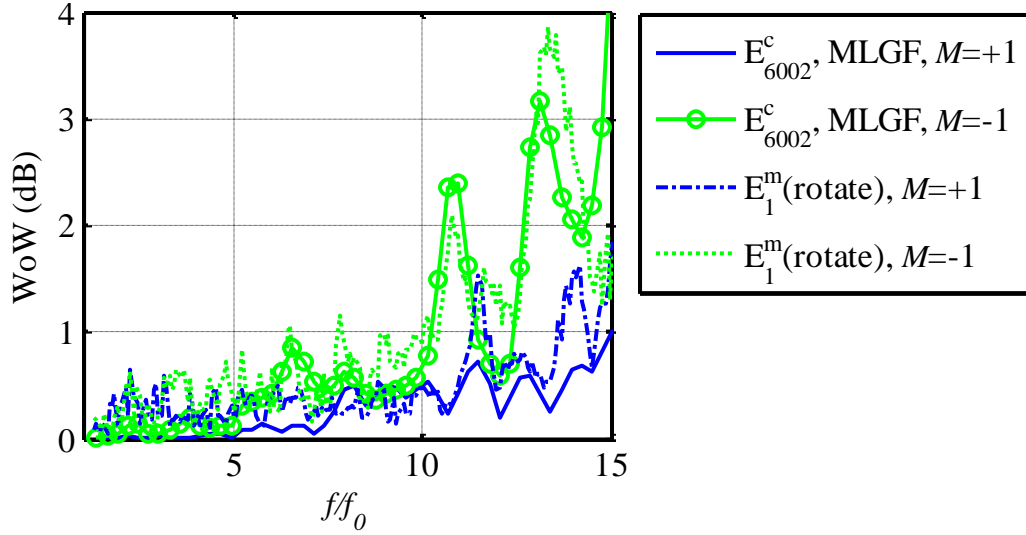


Figure 2.37: Forward ($M=+1$) and reverse ($M=-1$) WoW at $\theta = 30^\circ$ obtained using modeling (MLGF), and single arm measurements.

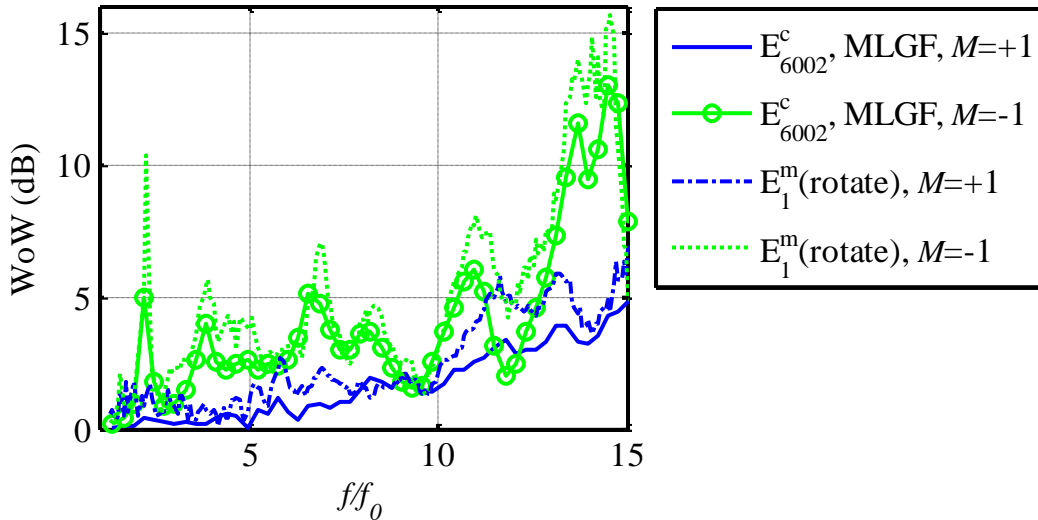


Figure 2.38: Forward ($M=+1$) and reverse ($M=-1$) WoW at 60° obtained using modeling (MLGF), and single arm measurements.

The cross-polarization predictions in Figure 2.39 also track the measurements well. Obviously, an optimized design would reduce the observed high axial ratio by using higher modulation and slower

expansion. The degradation in performance of the gain, WoW and cross-polarization at $2.25f_0$ is due to the MAW spiral termination. The antenna has an imperfect reflection when it cannot radiate efficiently and the reflection causes the observed high cross-polarization. With lower expansion factors the reflection decreases due to improved radiation efficiency.

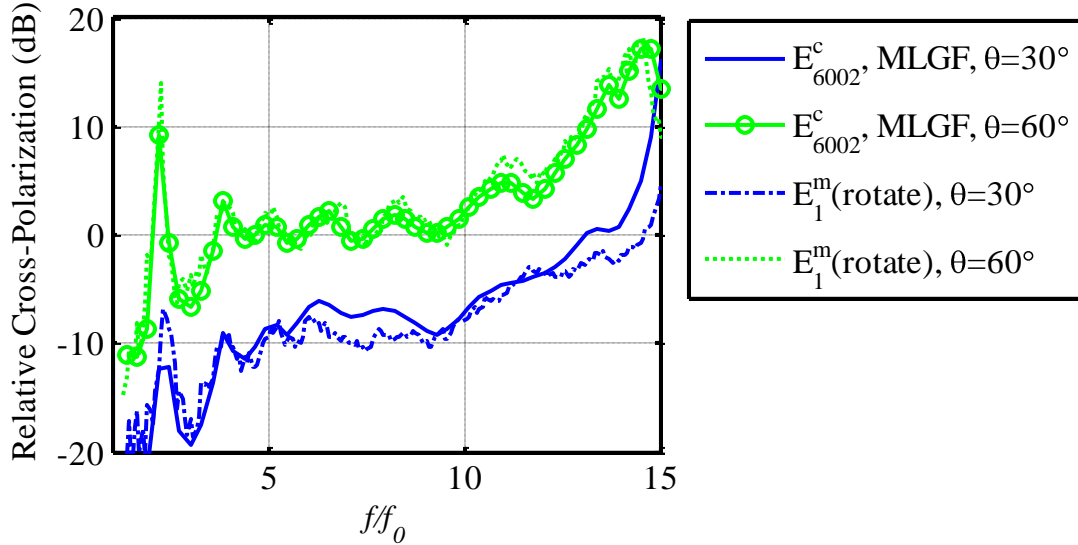


Figure 2.39: Cross-polarization for reverse mode at $\theta = 30^\circ$ and 60° obtained using modeling (MLGF) and single arm measurements.

However, a significant narrow band resonance can still occur if parameters are not carefully tuned. Similarly, as with log-periodic antennas, gain dropouts occur particularly where the termination (finite size) effects interfere with the active region. Computed and measured S-parameters for a 50Ω reference are shown in Figure 2.40. Due to the symmetry of antenna feed $S_{21}=S_{41}$ and only S_{21} is displayed. Good agreement between measurements and both computational models insure that the presented modal impedances have been computed correctly.

2.8 Conclusions

This chapter investigated dual polarized operation of a MAW spiral as a function of expansion rate, modulation ratio, feed and bandstop regions with some evaluation of alternate geometries. The MAW spirals under these conditions show good pattern purity for expansion factors less than 1.5 and modulation greater than 4. Other parameters including heavier dielectric loading, beamformer design and its imperfections, and cavity-backing have been considered but not detailed. Three different ideal beamformer composite measurements are devised for studying the antenna element. Good agreement with

full-wave predictions validates the presented results and conclusions. The performance of four-arm MAW spirals and several approaches for performance enhancement are studied and demonstrated. It is shown that the Archimedean MAW spiral exhibits improved far-field purity and more consistent patterns and impedances than the most commonly used equiangular MAW spiral. Deviation from the self-complementary principles by progressively increasing the width of the metal low-impedance sections (than at the same rate reducing the width of the high-impedance sections) can also enhance the far-field characteristics. It is shown that printing the MAW spiral arms on both sides of the substrate can improve the antenna performance in some areas. The importance of various parameters, including the separation layer thickness and modulation ratio is demonstrated and directions for the future research are denoted.

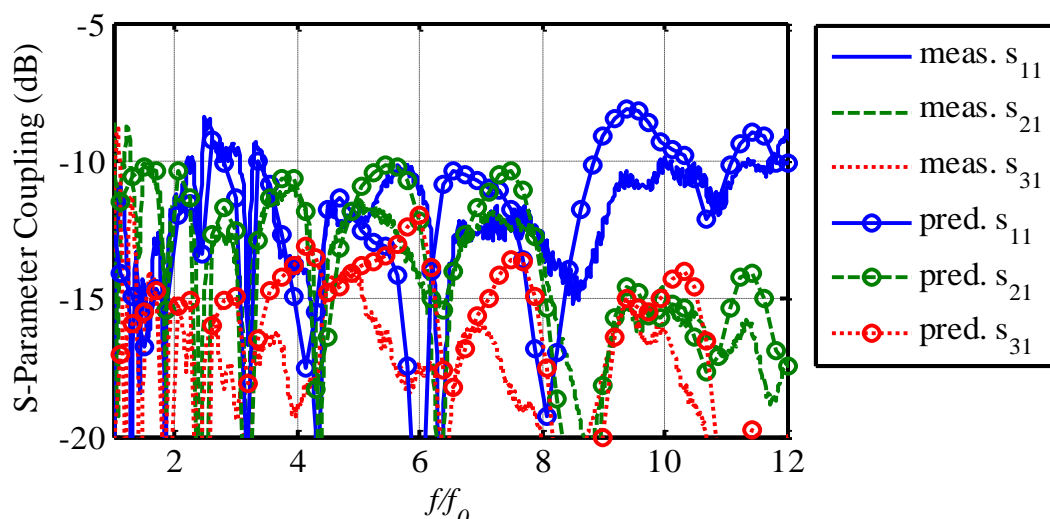


Figure 2.40: Predicted and measured S-parameters using HFSS [44].

CHAPTER 3

ANGLE OF ARRIVAL IN FOUR-ARM SPIRALS

Robust sensing of unknown signals typically requires the capability to detect orthogonal polarizations over wide bandwidths by a sensor occupying a small physical area. FI antennas discussed in this chapter have greater than 3 to 1 bandwidth, thus eliminating geometries using conventional TE_{10} waveguide horns, patches and similar relatively narrowband antennas. Ideally, the sensor should also provide capabilities such as estimating the angle of arrival (AoA) of an RF signal. Two techniques are commonly used in AoA, specifically, interferometry also known as time delay [60] and amplitude comparison [61]. In interferometer applications, the difference mode although not required is often desired to eliminate ambiguities due to interferometer processing [60]. The most commonly used conformal FI sensors are spirals and sinuous antennas with four-arm spirals dominating the AoA applications [61]. Note that two arm spirals can provide wideband AoA only in an interferometer configuration. The same is true for four-arm sinuous, however, a dual-polarization operation is an added capability. The four-arm spiral configuration enables the use of two modes that allow direct detection of AoA by forming a phasor voltage ratio between the modes. The resultant phase of the ratio provides the azimuth angle and the amplitude ratio provides the elevation angle (for the coordinate system shown in Figure 1.1). Polarization can be obtained similarly by ratio of the two polarization ports with phase providing tilt angle and amplitude providing axial ratio. The most efficient way to get both of these capabilities in one antenna will be to combine the beamformer of a four-arm spiral with a dual polarized element. When this approach is applied to a sinuous element, the resulting antenna has no dominant difference mode polarization, as will be shown later. Likewise, the spiral element filters out the opposite polarization, so it provides only location and not polarization of the emitter. While AoA historically has

been important for navigation in the detection of beacons, now the ubiquitous GPS system helps in most aerial direction finding. In a military situation the emitter will often not provide his coordinates and identification, therefore the information must be extracted by the radio emission to reduce the opportunity of surprise encounters.

In this chapter, we demonstrate that the four-arm MAW spiral can enable simultaneous detection of polarization like a sinuous antenna does, and the determination of direction like a four-arm spiral does. Thus, the MAW spiral antenna can support wide angle surveillance, active seeking of emitters, and provide a very small footprint both inside and on the surface of the platform replacing many detectors with possibly just one. The differential mode capability is different from interferometer applications of an antenna where a long baseline is required to achieve accuracy using time delay between omni-directional antennas.

Purity of the polarization performance for the MAW spiral sum mode has already been described in earlier work supported by measurements to a high level of accuracy [51]. A MAW is a specialized geometry subset of a generic spiral (normally equiangular) that allows the spiral to provide two orthogonal polarizations by the use of bandstops. Normally, difference mode is not used in a four-arm MAW spiral or sinuous antenna, but four-arm spirals routinely are used for AoA or direction finding [62]. Our investigations show that the MAW spiral will support difference mode operation with a dominant polarization determined by the wrap of the element. Therefore, in this paper we demonstrate how to achieve the difference mode (also known as mode 2) used for AoA as well as dual polarization operation out of a single four-arm antenna, thus utilizing three of the possible four excitations of the antenna element. This is an important finding which allows use of much simpler beamformers thus smaller cost, weight, and reduced size of the electronic support front-end, increased system bandwidth, sensitivity and dynamic range, etc.

3.1 MAW Spiral Capability

Since its inception, sinuous antenna has been a leading candidate for multi-octave, single planar aperture, dual-polarized radar warning and signal intelligence applications. While MAW spiral can

achieve similar performance, its potential for wider acceptance was tempered by the complex shape, decreasing tolerances, difficult design for good performance, and frequency spinning dual-linear polarization (when excited in this mode). A different delay and dispersion for each polarization of a MAW is another difficulty that needs to be addressed. However, a four-arm MAW spiral is still a spiral and thus it should provide a good single polarization difference pattern. Thus, in spite of the fact that open literature does not discuss this mode of operation the MAW spiral could have capability not available in four-arm sinuous antennas. A major concern is that the circumferential location for the difference mode is the same as the bandstop, which can degrade the polarization purity of mode 2. In addition, the difference mode would have the same phasing for both polarizations at the feed, so polarization is only separable into right and left for a spiral geometry that forces the cross-polarization to propagate outward. With the MAW, the outward propagating mode will almost immediately reflect off the bandstop and return to the feed point with the same delay as the inward propagating mode. Since MAW antennas are not normally terminated to maximize bandwidth, the polarization purity is degraded and currents that propagate to the end of the spiral will be reflected back to the feed point even further contaminating pattern performance. As the previous chapter has demonstrated, it is difficult to accomplish the same polarization purity and loss with a MAW spiral because the element rejection of polarization is limited by the bandstop efficiency since the cross-polarization is generated before passing through the radiation region to the beamformer. For a sinuous antenna most of the cross-polarization is a result of the beamformer, unfortunately for a four-arm geometry the difference mode provides the same phasing regardless of desired polarization meaning the element provides whatever polarization control is possible for the antenna.

The results presented here will show that the MAW spiral behaves like a slightly degraded conventional spiral in the difference mode. Also, the geometry is an efficient radiator and provides a clearly dominant polarization based on the element wrap rather than feed point phasing enforcement alone like a sinuous antenna would. This wrap results in a MAW spiral with three useful modes. A single aperture AoA may be enabled by utilizing the two calibration surfaces to improve instantaneous beam split over the conventional two port, single polarization design with no knowledge of the emitter

polarization. This approach however requires frequency detection to allow the resulting surface search with polarization compensation. Note that the sinuous antenna has a difference mode, however the polarization is not filtered by the geometry leading to a frequency dependent polarization flipping between left and right or vertical and horizontal. The polarization rotation results in the sinuous having no single valued AoA solution at a single frequency.

The third mode on a four-arm equiangular or Archimedean spiral is a difference mode peaking at a wider angle in elevation (θ) and having an extra cycle of phase in azimuth (ϕ). The additional mode can increase angular sensitivity of a spiral, but will not help polarization blindness or provide emitter polarization information. Polarization detection requires the antenna to detect almost orthogonal polarization on separate ports at a known angle, since the phase between the two polarizations changes based on the direction of arrival due to polarization. The third mode is also only useful above $3f_0$ (f_0 is the cut-off frequency of the lowest mode of the spiral). Based on the behavior described, the MAW spiral is a good compromise between complexity, beam types and polarization when placed in a proper perspective to the sinuous and the AoA spiral. The MAW will require more calibration than the other geometries, because of its frequency dispersive property and higher pattern ripple.

For a conventional AoA spiral the delay between the sum and difference can be optimized to allow nearly constant phase delay between the modes independent of frequency over a bandwidth of up to 3:1. Note that for a MAW, it is necessary to have good knowledge of the antenna patterns for improved sensor performance and to increase knowledge of the emitter. Without any detailed investigation into the effects of polarization, if frequency is known the beam split (direction resolution) statistic should improve by a factor of three in azimuth due to the phase between the two sum modes being three cycles instead of one cycle between the sum and difference modes. Meanwhile any ambiguity is resolved by the ratio of sum to difference in the same polarization which is typically single valued over the field of view (FOV). Improvement in elevation resolution will be small since the two sum modes have similar patterns in elevation. When using the MAW for AoA without frequency detection, however, the obvious ambiguities of phase due to polarization and frequency must be addressed.

This chapter studies a dual-polarized four-arm MAW spiral antenna with difference mode capability. Use of the difference mode with four-arm spirals been extensively investigated and its applications to AoA are well established in [6365]. This work demonstrated that the conventional four-arm spirals provide a consistent difference mode especially when frequency calibration is applied to the pattern. It is also shown that this feature is not available in the most commonly used dual polarization sensitive antenna, a four-arm sinuous antenna.

Dual polarized AoA can be achieved over approximately a 2.5:1 bandwidth using the inside and outside fed four-arm spiral [66]. Bandwidth can be increased by adding additional arms to the spiral. However, in addition to the limited bandwidth, especially in the mode 1 outside case, two separate beamformers are needed, one for each side of the antenna. To achieve FI-like performance over a much wider bandwidth, both polarizations must be obtained by a center fed antenna due to the inability to control modes above 4 when the antenna is fed from the outside. A common embodiment addressing this issue is a sinuous antenna. The four-arm sinuous antenna is usually feed by two Marchand baluns one for each pair of opposite arms. Circular polarization is then created by beamforming the two orthogonal linear polarizations through a 90° hybrid [67]. The component is also produced without the hybrid providing dual orthogonal linear but frequency oscillating polarization. However, the sinuous antenna can only control two modes (1, -1) by this method. The results presented herein show that when adjacent arms are fed 180° out of phase for the four-arm sinuous, the pattern is not distinguishable as either mode 2 or -2, although the broadside null is well defined because neither mode has power at broadside. Thus, the element itself has no polarization preference, and its usefulness for AOA is questionable at best.

For an ideal AoA sensor, a simple transform between the measured voltage of an antenna and the direction of the signal can be written mathematically with a monotonic function in two variables for direction, independent of polarization and frequency. Note that in this chapter, the antenna is placed in the XY plane with broadside radiation pointing to the positive Z. In a conventional monopulse system, the azimuth response corresponds to the phase difference between the sum and difference channels. The amplitude of the ratio for the same two channels corresponds to the elevation, removing the need for

knowledge of the emitter power. This relationship can be applied to numerous multi-port antenna designs. In particular, a four or greater arm spiral provides access to the desired sum and difference modes because only one mode will provide a sum pattern of the available excitation modes, all other symmetric modes adding to zero in the polarization imposed by the spiral wrap on broadside. Unfortunately, the arc length of a spiral to the radiation region for the sum and difference modes is not constant over frequency. While an algorithm for a spiral with constant delay to achieve this response has been described, it is physically unrealizable over bandwidths exceeding 2:1 because the length of the spiral must remain constant between the circumference of λ and 2λ where λ is the wavelength of the signal [63]. Although an exponential spiral has the same number of wraps for each size doubling, the arc length increases exponentially and to have a constant arc length in wavelengths the rate of growth must increase rapidly as the spiral increases in diameter to keep the electrical delay constant. This approach is first, not an equiangular spiral and more importantly, not physically realizable in a frequency independent antenna because the number of wraps increases as the spiral diameter decreases to keep the delay constant.

However, if the assumption is that the detector for the spiral will have limited bands to improve sensor sensitivity, an expansion factor of 1.5 for a spiral can be matched over approximately 2:1 bandwidth without modifying the growth rate. Since the arc length grows exponentially, the lower the growth the less phase error across the bandwidth if compensated by a linear delay line. Under these circumstances, each detector can introduce an appropriate offset between the sum and difference mode to ensure an approximately constant azimuth response. While the concern can be eliminated if the emitter's frequency is known, the frequency detection is a more complex activity than just ratio of voltages. The layouts of the three evaluated geometries, specifically MAW spiral, sinuous and conventional spiral antennas are shown in Figure 2.1. All performance results are shown as a composite plot of 72 angles in azimuth (5° separation) at a fixed elevation angle thus allowing qualitative assessment of antenna's solid angle pattern (symmetry, cross-polarization, etc.).

To evaluate the performance of these three antennas as truly FI, the scan angle is fixed to a constant and the pattern stability in ϕ is examined. The angle chosen for the Figs. 3.1-3 is 30° because for

AOA to be useful the pattern must be stable over a reasonable solid angle. In addition, to ensure that the response is unique over this solid angle, it is desirable that the average difference pattern response in θ be monotonic to prevent ambiguities. Because 38° is the approximate peak of $M = 2$, the chosen angle of 30° should be nearly ideal to evaluate the pattern properties for possible AoA use inside the range if the ratio is single valued. The primary polarization is right hand circular based on the spiral wrap. Mirror images of the three elements would flip the dominant polarizations, but otherwise the results would be the same.

All three geometries do excellent jobs of providing an omni-directional pattern in sum mode operation as shown in Figure 3.1. A co polarized right-hand circularly polarized (RCP) gain at 30° for all three geometries is shown in Figure 3.1(a). As seen, the gain of these antennas is very stable and similar over almost a decade bandwidth. As expected, the conventional spiral has the smoothest gain variation as the outward propagating current faces no reflections from bandstops (MAW) or turns/bends (sinuous). Respective cross-polarized gain for these antennas is shown in Figure 3.1 (b). The cross-polarization rejection of at least 25 dB is observed for all antennas indicating a wide-beam, polarization pure mode 1 in the far-field.

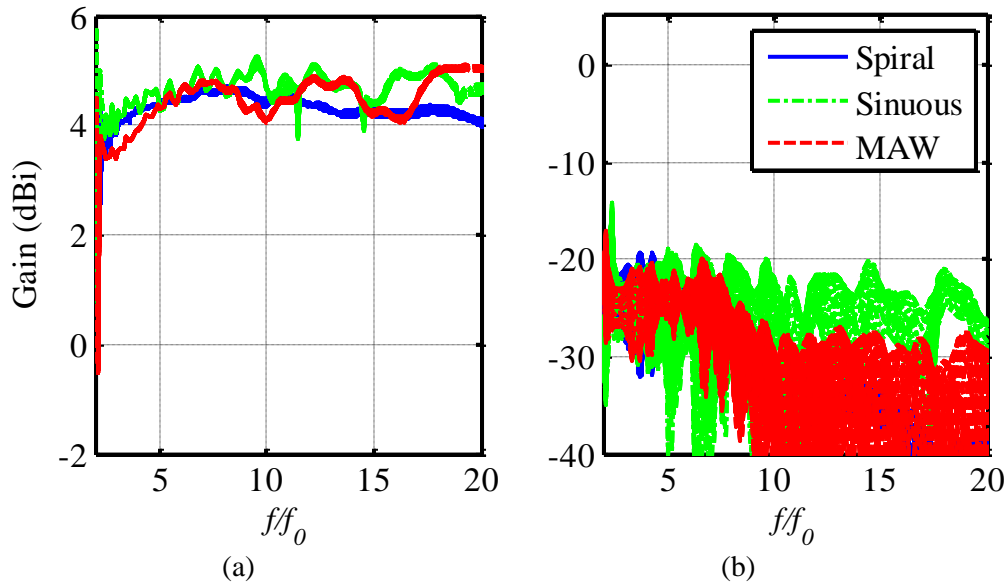


Figure 3.1: Gain of antennas in (a) RCP sum mode at $\theta = 30^\circ$, (b) x-pol of sum mode operation.

Difference (mode 2) RCP gains for the antennas from Figure 2.1 are shown in Figure 3.2. As seen, the sinuous antenna has a linearly polarized difference mode (since the response is the same for both right and left circular except for the cycle start). Moreover, the polarization of a sinuous antenna is

unstable limiting severely its usability as AoA sensor. On the other hand, conventional smooth spiral has a polarization pure and stable pattern, while MAW spiral has clear handiness of its pattern with cross-polarization of -10dB or better. The tight spread of the gain curves indicates good pattern symmetry of the antenna.

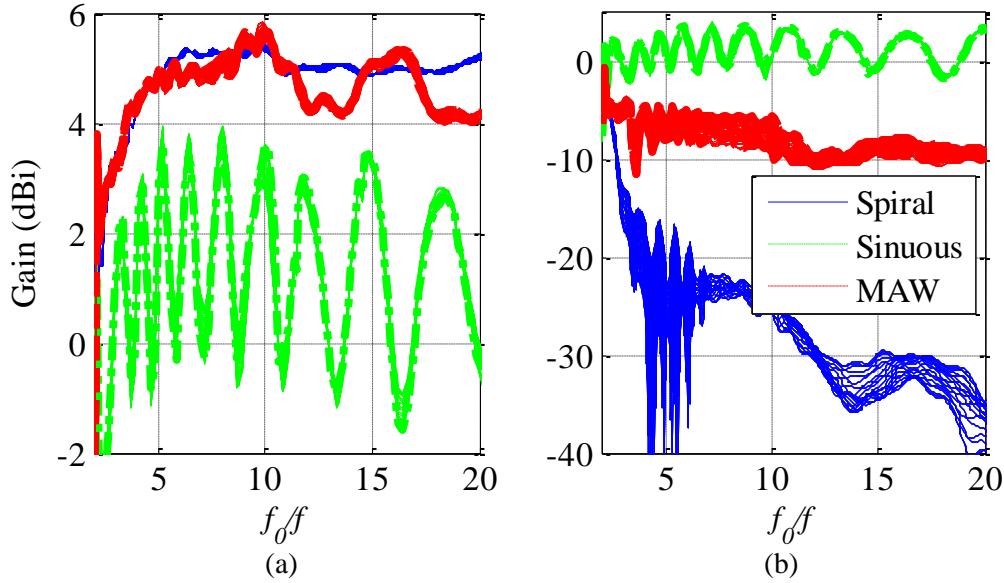


Figure 3.2: Off axis $\theta = 30^\circ$ (a) co-pol of difference mode, (b) x-pol of difference mode.

The gains for LCP sum mode, reverse of the spiral wrapping sense, 30° off axis for the three studied geometries are shown in Figure 3.3 (b). As seen, the conventional smooth spiral has extremely limited dual polarization sum mode operation over less than 2:1 bandwidth. Above about $2.5f_0$ the spiral starts to radiate RCP mode 3 efficiently. On the other hand, the MAW spiral and sinuous both have good mode -1 gains. The LCP gain for the smooth spiral and RCP gains for the MAW and sinuous are shown in Figure 3.3. As seen, the conventional spiral response above $3f_0$ occurs in the undesired polarization for determining emitter polarization. In addition, the cross-polarization of the MAW spiral is not as good as that of a sinuous, however, the level of 15dB or better is sufficient for the above-mentioned purpose.

The spiral only provides dual polarization below $2.5f_0$ as shown in Figure 3.3. Above $2.5f_0$, the polarization for $\mathbf{M} = -1$ is the same as $\mathbf{M} = 1$, meaning the spiral is operating in $\mathbf{M} = 3$. While the sinuous will typically outperform the MAW spiral in reverse mode polarization purity, as shown in Figure 3.3, the amount of difference is controlled by the expansion and modulation rates. Polarization for the MAW will be similar to this sinuous if $\text{EXP} = 1.25$ and $m = 8$, although maintaining some of the MAW features

would be difficult with the required 1000:1 ratio on the smallest details to overall size.

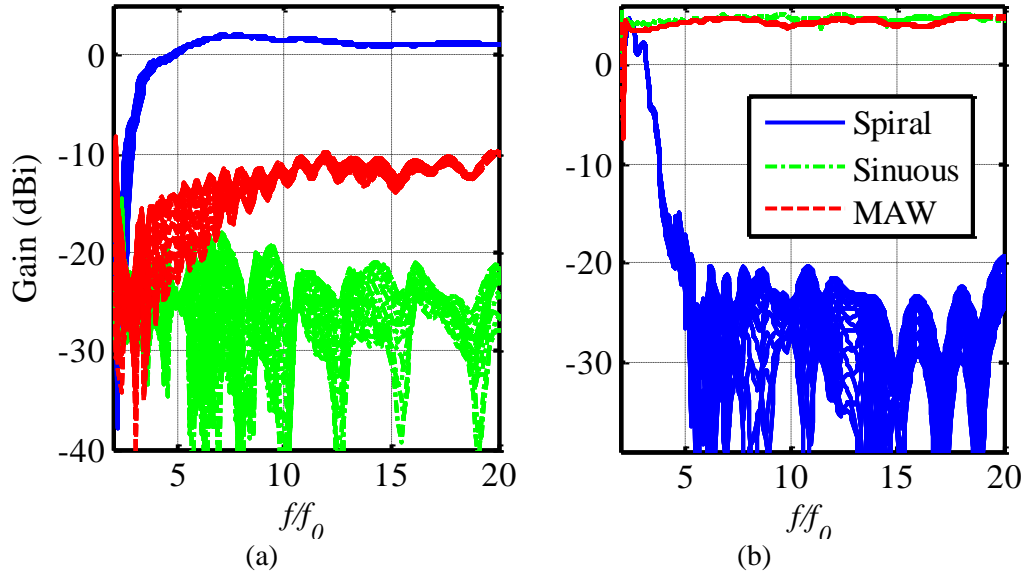


Figure 3.3: Off axis $\theta = 30^\circ$ (a) co-pol of reverse sum mode, (b) x-pol reverse sum mode.

The polarization of the MAW spiral in the difference mode is sensitive to the modulation parameters. However, in order to reduce significantly the cross-polarization response, the modulation needs also to be reduced to the point that the reverse polarization mode response is highly degraded. As seen from the above figures, the only geometry that enables polarizations tracking between the sum and difference patterns, and polarization diversity is the MAW. A simple beamformer constructed of one 90° and three 180° hybrids is needed to obtain all three modes of operation. Note that the traditional implementation calls for at least 5 arms (8-arms is typical) which also requires a significantly more complex beamformer. The hybrids are available as commercial off the shelf (COTS) devices or can be readily designed for performance optimization in most parts of the microwave band.

3.2 Place for MAW Spiral in the FI Antenna Family

The commercially available antennas that would be considered alternate solutions for the application discussed herein using the MAW spiral, are the sinuous and equiangular spiral, each of which has their own limitations, especially when restricted to four-arm geometry. The fourth planar conformal geometry, i.e. the log periodic, will not be discussed as it will not introduce any benefits when compared to the sinuous. All considered antennas belong to the class of frequency independent antennas.

Modulation to the base spiral is done by adding and subtracting the angular offset at the

appropriate period (90° for a four-arm spiral) to ensure the periodic geometry is self-complementary. By making the arm modulation a function of ϕ , the antenna is kept FI because its structure is not described by any length criteria. The amount of modulation of the angle is referenced to a maximum range of $\pm 22.5^\circ$ for a four-arm spiral. Each arm of the four arms has two sides and the total cannot exceed 90° for a possible variation of up to 45° for each curve. Thus for a modulation ratio of 8, the edge of a spiral arm switches using the modulation function by $\phi_0 = \pm 17.5^\circ$ offset from the nominal curve. The geometry created leads or lags the parent curve, leading to a 10° gap where the impedance is low and an 80° gap where the impedance section is high. Transitions from high to low impedance sections are step functions in ϕ , though the transition could be implemented using different mathematical functions as in patents [22, 23], however it has yet to be proved that any work better than the step impedance. The requirement to keep the spiral self-complementary will have adjacent arms synchronize at a period of $360^\circ/N_{\text{arms}}$ or $\phi = 90^\circ$ for the four arm case. When this period is chosen, consistent frequency independent impedance is ensured by symmetry. However, if the period is changed to either less than or greater than $\phi = 90^\circ$ for a four-arm spiral, the self-complementary behavior disappears. The self-complementary relationship will return at periods of 2, 6 and 8 due to the structure periodicity. Note the basic spiral is generated when the modulation function is unity. The sinuous is obviously not from the same topology because $f(\phi)$ is not continuous through a full rotation of ϕ . The MAW spiral antenna is based on this clear geometric similarity to a conventional spiral, and has no apparent reason to not provide an existent, stable $M = 2$. Until now, this behavior must not have been completely clear, as it has not been mentioned previously as a useful mode of operation.

Figs. 3.4-6 show the front hemisphere response of the elements in Figure 1.1, starting with the MAW spiral in Figure 3.4. As predicted, the model shows a well-behaved $M = 2$ in the center plot. Figure 3.6 shows that the spiral has a very consistent pattern, but only one polarization for FI operation. As expected, the sinuous has a slant linear response, as shown in Fig 3.5 (b), where RCP and LCP match. The four-arm sinuous antenna has a dual polarized radiating element with no dispersion between the two polarizations of operation, but has an oscillating polarization tilt angle and no useable difference mode.

This means for a sinusoid to perform AOA, it either needs one of two implementations. One is to array the four-arm sinusoid and use interferometry techniques to separate the phase delay between the multiple antennas. This solution is more complicated than the simple voltage ratio proposed for the MAW and prone to ambiguities if the wavelengths become smaller than the element spacing divided by the sine of the angle off broadside. An alternate solution increases the total arm number to at least six, which also increases weight, relative loss and complexity of the Butler matrix feeding the element, while also increasing the arm interaction and the impedance variation caused by the arm coupling.

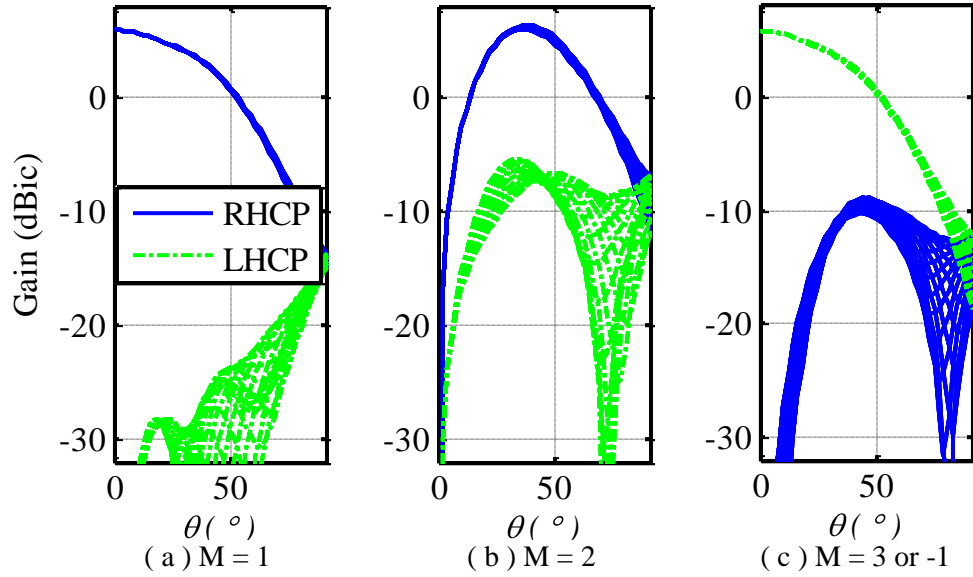


Figure 3.4: Patterns at $10f_0$ of a four-arm MAW spiral.

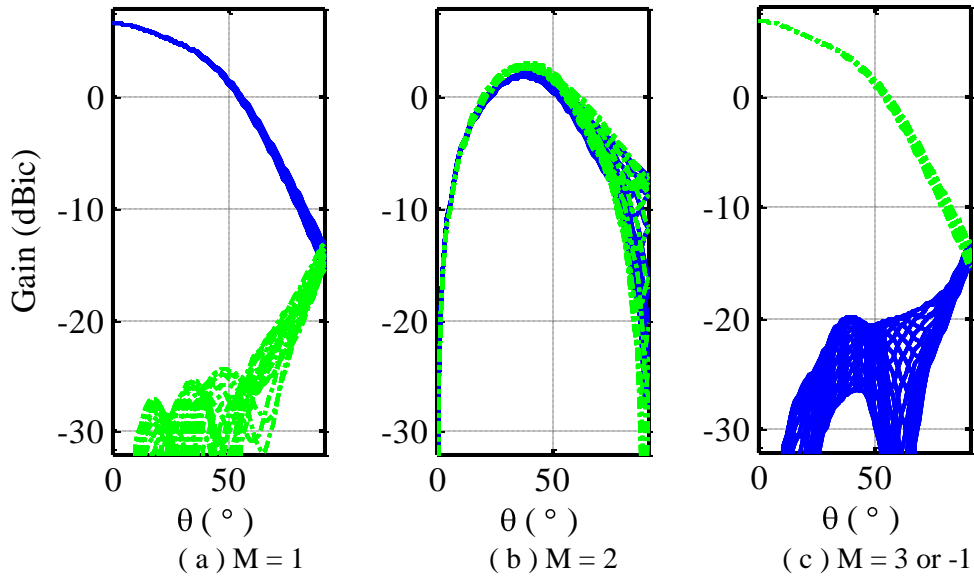


Figure 3.5: Patterns at $10f_0$ of a four-arm sinusoid.

While the equiangular spiral and the MAW spiral produce similar difference patterns, the spiral has no way to sense polarization. The addition of a second antenna with the opposite arm wrap to produce the second polarization is required. While the basic accuracy of this design would be better than a MAW spiral due to polarization purity, extracting the polarization between the two antennas would require removal of the interferometer phase. In addition, processing an additional reference channel to ensure the same signal is processed on both antennas may be needed.

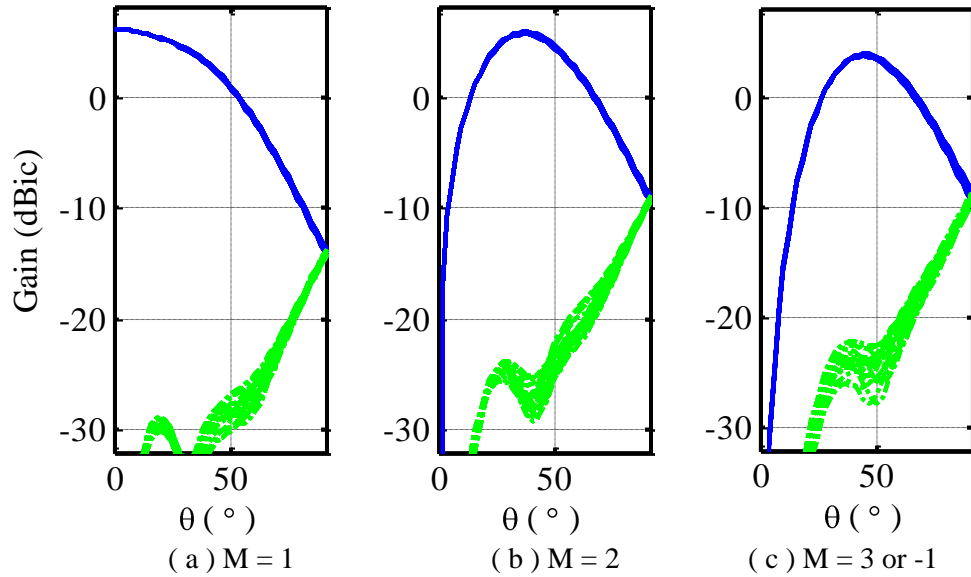


Figure 3.6: Patterns at $10 f_0$ of a four-arm spiral.

Among conformal FI antennas, the MAW provides the simplest solution for instantaneously measuring both polarization and AOA. As with most solutions, the antennas each have their advantages, but the alternates provide a more complex solution for complete polarimetry than the MAW spiral.

The MAW compliments the other two antennas for use based on its ability to provide both useful capabilities (AOA and polarization), although it is not as proficient as either the sinuous or the equiangular spiral in supporting their individual capability. For AOA, both the MAW and the equiangular spiral have the same dispersion, which requires frequency compensation. For polarization detection, while the sinuous is not dispersive between its two polarizations it is still dispersive across frequency, resulting in signal distortions that may exceed the MAW's in some applications.

The interesting aspect of combining polarization and direction sensing is the completeness of the useable modes for the four-arm FI antenna. Mode 0 (equivalently 4) is excluded from radiating due to no

potential between the transmission lines that form the feed. The remaining modes are used to extract field information on a received signal, usually by making an analog equivalent of a FFT. The field is completely defined by power, polarization and direction. It would be ideal to have an antenna that can sample as many properties of the field as it has ports. With the fully implemented four-arm MAW, the resulting phasor signals, once frequency is known, provide a unique response for any incident field from just three measurements. The only ambiguity is when the polarization is cross-polarized to the difference mode. The three modes used would be $M = -1, 1, \text{ and } 2$ (same except for wrapping in either direction).

One obvious problem with the mode 2 operation was that the control of polarization was insensitive as shown in Figure 3.7 (b) for the parameters of expansion factor and modulation ratio. The cross-polarization of mode 1 in Figure 3.7 (a) can easily be controlled by these same parameters over at least a 15 dB range to allow the designer to select loss versus pattern symmetry. In Figure 3.7 (b) using the same geometric method to control polarization yields only 2 dB of variation. Thus, it would be good to develop an alternate method to control polarization of mode 2.

3.3 Mode 2 Cross-Polarization

The contamination of the cross-polarization of the mode 2 operation due to the reflection of the currents off the bandstop is depicted in Figures 3.8 (a) and (b). Interestingly, the delay between the cross-pol and co-pol mode is negligible, which is the result of having the radiation region collocated with the resonant length of the band stop. If the polarizations were dispersive due to their different modes like modes 1/-1, then gating could be used to improve the polarization, unfortunately that is not the case for mode 2 operation. For the dual polarization operation of the four-arm MAW the dispersion between the two sum modes is large due to the different path lengths between the feed and active region. High modulation ratio and low growth rate will assure that the sum modes have circular polarization with a good beamformer.

3.4 Beamformer Requirements for Four-arm Geometry

If the four-arm device is being excited by use of a beamformer, the complete component configuration is shown in Figure 3.9. This beamformer is a fully populated Butler Matrix,

equivalent to a four point Fast Fourier transform. This type of beamformer is required to generate both sum and difference modes. For the simpler requirement of only mode -1 and 1, the third 180° hybrid can be eliminated (in the top right corner of Figure 3.9). Another simplification, usually done when the difference mode is not required, is to replace the first and second 180° hybrids with Marchand baluns to convert the coaxial line to a balanced feed line. This approach will reduce loss and cost for a mode that is not being utilized. This beamformer can be used to feed either a sinuous or a MAW spiral for dual polarization applications. The results in the following section show additional statistics on the three FI antennas if full Butler matrices are used with four-arm geometries.

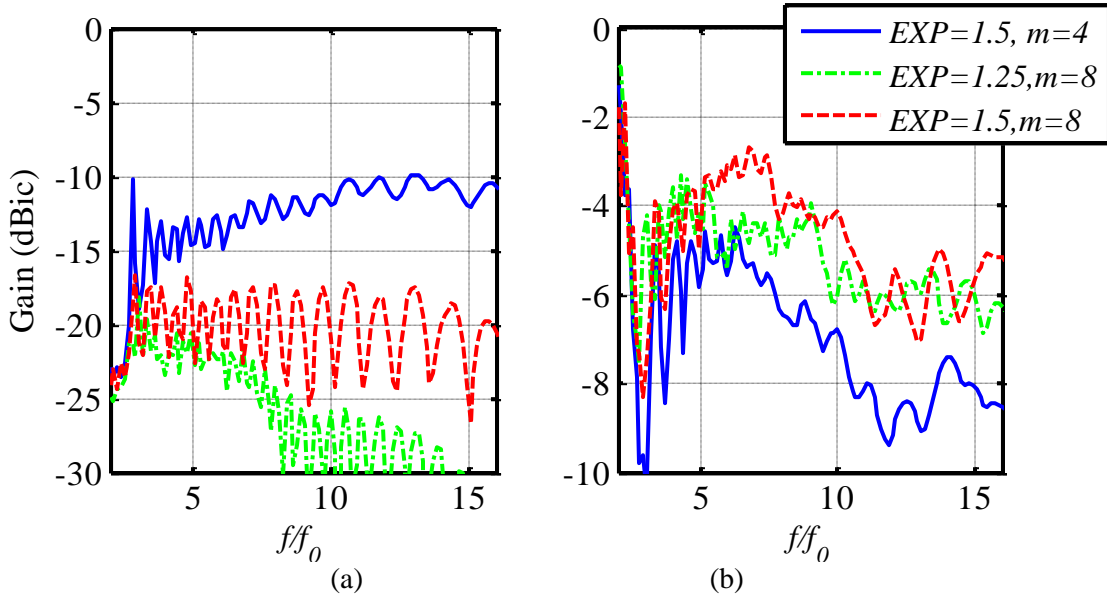


Figure 3.7: Comparison of mode -1 (a) and mode 2 (b) cross-polarizations for three MAW spiral geometries at $\theta = 30^\circ$.

The requirement for a difference mode, as encountered in AOA spirals, repopulates the BFN from the sinuous antenna case, which results in increased loss over the single hybrid implementation. Obviously, the modal purity of the beamformer will contribute to the overall performance of a physically realized antenna. This behavior can be expressed analytically as cross-modal contamination of the three radiating modes, given the single arm response. The final, all in-phase, mode is treated as additional loss since the element cannot radiate mode 0 or 4 efficiently.

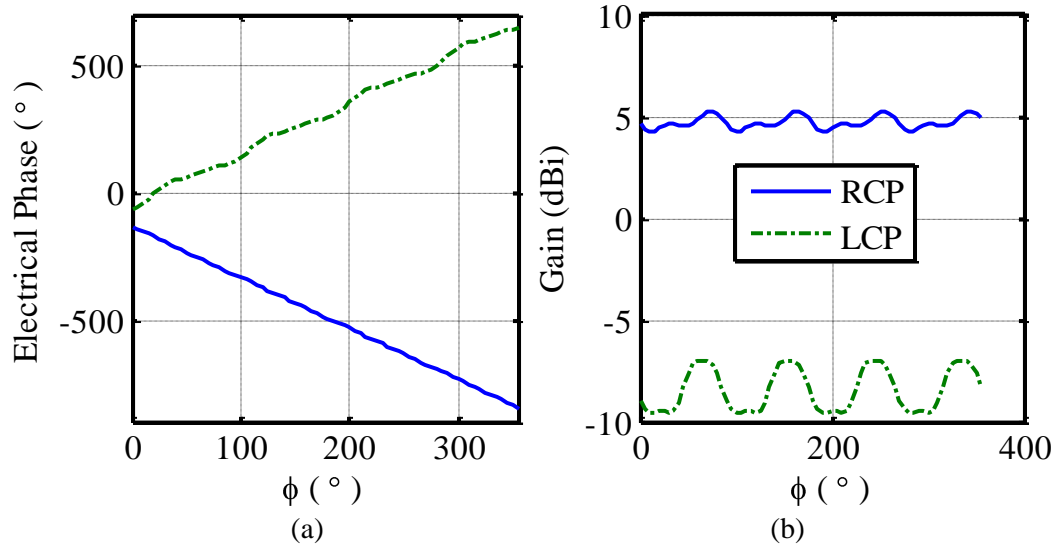


Figure 3.8: Mode 2 at $14 f_0$ (a) phase progression and, (b) gain of each polarization.

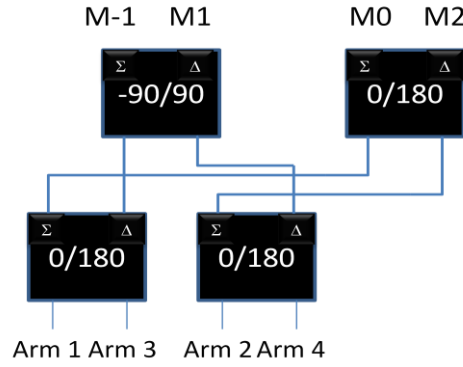


Figure 3.9: Butler matrix beamformer for a four-arm spiral, MAW spiral and sinuous antenna.

We claim that the MAW spiral provides the best functionality for a four port Butler geometry utilizing three of the four available modes. Below, the performance of the other more commonly used FI antennas are compared to the MAW spiral. The performances demonstrate the expectations of a typical design for each FI geometry.

3.4.1 Orthogonal Behavior of Modes

A MAW spiral is characterized by the different delay for the two polarizations. In addition, the delay is dispersive; as the frequency decreases the delay increases. This prevents the use of a simple delay line for improving the tracking between the two modes over frequency. Note that the true monopulse operation is desired, because it removes the need for accurate frequency detection as part of the initial electronics. This is of course more complex than the use of a reference signal from one port of the antenna

to measure relative phase and amplitude relationships.

Unfortunately, having a completely analytic function used to map the response between AoA and the antenna coordinate system is not possible, although over a limited FOV this result can be approached since the response linearizes locally. In the particular case of the monopulse MAW, due to mode 5 and 6 or ± 3 and -2 in the opposite polarization contamination, especially at wide angles, the function has at least a low order modulation with a 4-fold symmetry caused by poor suppression of these additional modes that cannot be eliminated by a four port beamformer. This contamination causes WoW. Because WoW is an easy to understand but non-standard antenna parameter, WoW is subscripted here by the emitter matched polarization variation of the antenna pattern at constant θ in ϕ rotation, which more directly described the response of the sensor. The larger is the WoW the lesser is the accuracy of a classic monopulse. The poor pattern purity as opposed to polarization purity corresponds to an uncertainty in the readout of the elevation angle. The WoW at 30° for the three studied geometries is shown in Figure 3.10. As seen, the MAW spiral has performance similar to the conventional smooth spiral, which is the best one can achieve for circular symmetry. Even in the polarization that would be matched to the sum port, the largest variation in mode 2 is for the sinuous antenna, although it is small. However, it is unlikely that the emitter is transmitting matched polarization. Therefore, the same statistic was then evaluated across the three antennas for a linear polarization; in this case the polarization was θ oriented, but the result would be similar for any linear polarization due to the nature of the patterns of all three antennas.

The effective pattern variation for a typical linearly polarized emitter is shown in Figure 3.11. As seen, for the same metric with the ratio of the sum and difference modes, the conventional smooth spiral performs the best because the polarization is almost identical for the sum and difference patterns. The small degradation in the spiral WoW below $4f_0$ is expected due to the reflections from the arm termination of the spiral causing ripple in the linear polarization (in this case an open termination). It is important to note that the actually fabricated spiral will have degraded response due to fabrication tolerances in the feed and beamformer [67]. The MAW spiral WoW performance is consistent with the observed 14 dB cross-polarization in Figure 3.2.

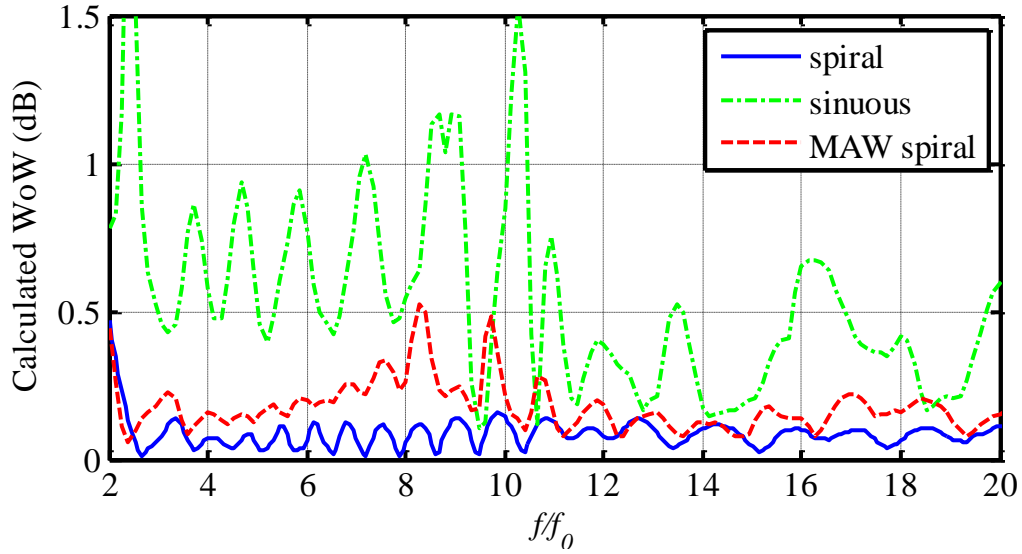


Figure 3.10: WoW_{rcp} of mode 2 at $\theta = 30^\circ$ for RCP (co-polarized).

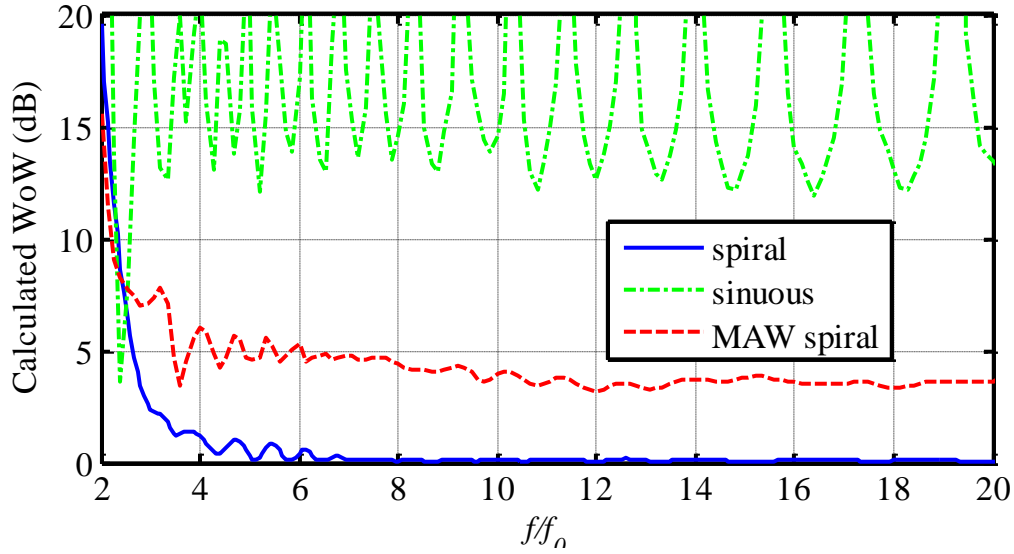


Figure 3.11: WoW_θ for θ linear polarization in mode 2 at $\theta = 30^\circ$.

Finally, the WoW of the four-arm sinuous antenna is very high, clearly showing its uselessness for analog AoA due to the inconsistent ratio of the sum port which will have almost no variation due to WoW and the difference mode which can have any value depending on the ϕ direction of the field. Considering this is the metric that would be used to estimate position in θ , it would be difficult to get a useable response even with a frequency table of the pattern because the positional solution would be fairly unstable. Even the 4 dB WoW of the MAW spiral would represent a much larger beamsplit than the spiral, although the increase in WoW for a fabricated MAW should be much smaller than that of the spiral due to already having the pattern limitations. This performance limitation did cause us to examine

methods to better control the MAW spiral polarization because the element was providing some filtering capability.

3.4.2 Parallelism of Modes

To excite the modes examined above a beamformer was needed, and the best way to inspect the idealness of the beamformer is to determine the contribution of each of the antenna ports to the output modal port of the device. By using standard S-parameter measurement techniques and the modal summation equivalent to an FFT with a factor for power conservation, the result in Figure 3.12 was obtained on the beamformer pictured in Figure 3.13, which also shows the antenna tested.

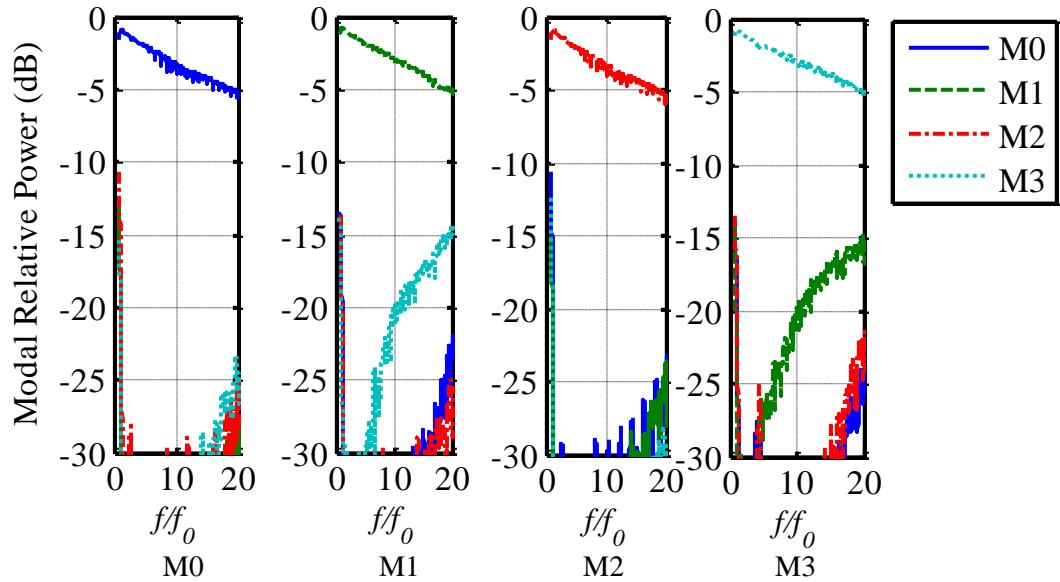


Figure 3.12: Measurement results for beamformer constructed from commercial hybrids shown in Figure 3.13.

Although the quadrature hybrid has a bandwidth limitation evidenced by these results, the modal isolation was still 10 dB at 20 times the nominal frequency, the chief source of performance degradation being the internal loss of the device, which can be compensated as appropriate for the comparison to the model predictions. Interestingly, because the beamformer match was dominated by the same internal reflection on all four ports, the power reflected back to either the antenna or the input was very small, typically less than -35 dB in any of the operational modes. The in-phase mode did show a significant reflection varying somewhat with the received mode between -20 and -6 dB of the received power. This mode is of no significance to the antenna because it also rejects most of the mode 0 power. Even though

the beamformer is not matched to the antenna impedance this result shows that the power is not reflected from anywhere internal to the beamformer back into the antenna making the 50Ω port used in the model consistent with the measured response of the antenna. Response from the inputs of the beamformer was not shown. There is also no requirement for phase matching on the device inputs, and the modal isolation is established by Figure 3.14 as being extremely high except for mode 0.

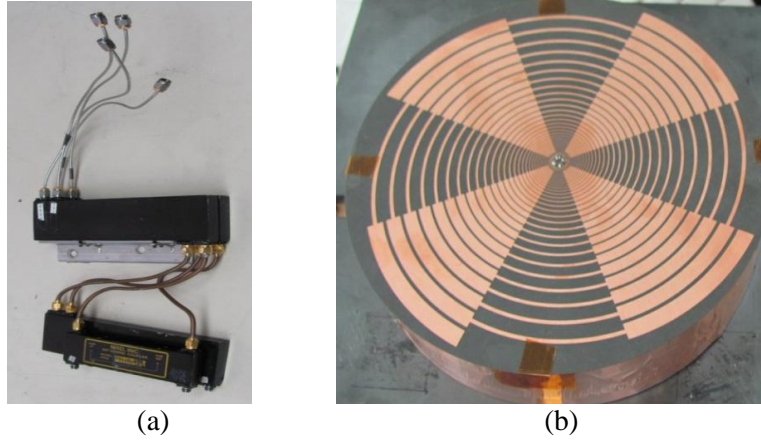


Figure 3.13: Picture of the (a) assembled beamformer from COTS hybrids and (b) AoA self-complementary MAW spiral with 4:1 modulation and expansion factor of 1.5.

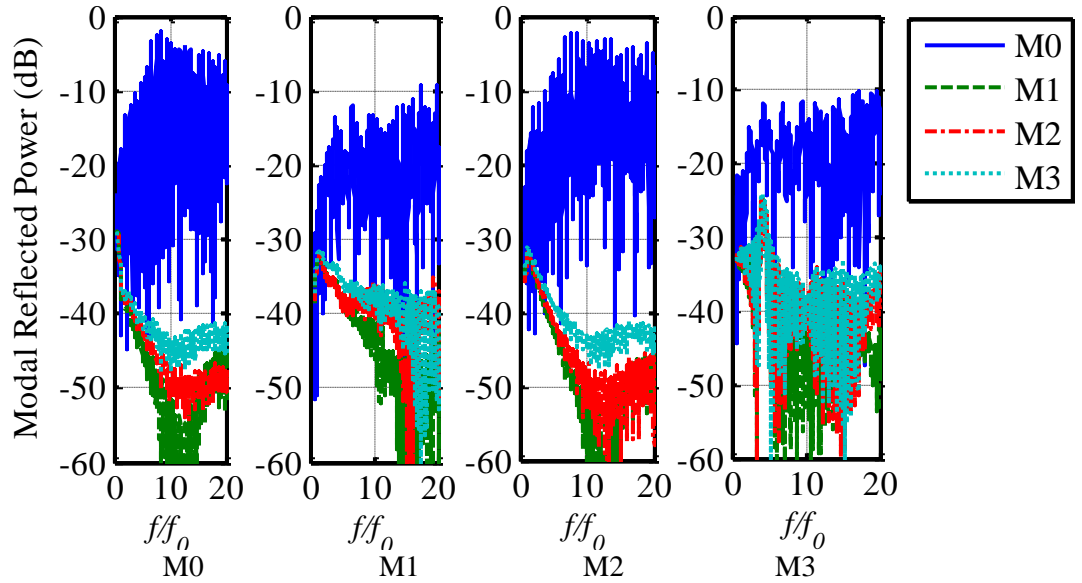


Figure 3.14: Power reflected into antenna from beamformer.

The delay between the sum and difference modes is shown in Figure 3.15 after being compensated by a constant delay and for ϕ of the position for a measurement 30° off broadside. The majority of the delay was removed with a simple delay line, as it would be in an AoA system. The

remaining delay is due to the exponential growth of the spiral (MAW or equiangular). If the sensor is sectioned into smaller bands the response will become more linear with frequency. If one inspects the area between 6 and $10 f_0$ the systematic error is less than 50° . The multiple traces are the residual error of each antenna to a linearly polarized signal. For co-polarized case, the vertical spread is greatly reduced on the MAW spiral, which is the AoA error of the sensor without polarization compensation. If the frequency is known, the vertical spread at a single frequency is the total AoA error for a linear polarized signal for each antenna. Without polarization compensation to help eliminate mode-2 contamination the error of the MAW spiral is much larger than the equiangular spiral.

The statistics of the theoretical AoA operation for two spiral antennas, linear polarization, and use of a delay line of $0.4\lambda_0$ is shown in Figure 3.15. Due to the high number of cycles in the surface of phase for any of the three modes relative to the others there is no unambiguous value for a signal of arbitrary frequency and polarization. While the operation of the four-arm MAW spiral in the sum mode for both polarizations is documented, the mode 2 performance is not documented. Mode 2 performance provided an acceptable difference pattern, which is not as circularly polarized as that of modes 1 and -1. However, it is highly unlikely that the MAW spiral even with one polarization in difference pattern is blind to the main beam of an emitter since few emitters will be truly cross polarized to the weak circular polarization of the MAW spiral difference mode, unlike an equiangular spiral for which all polarizations are the same.

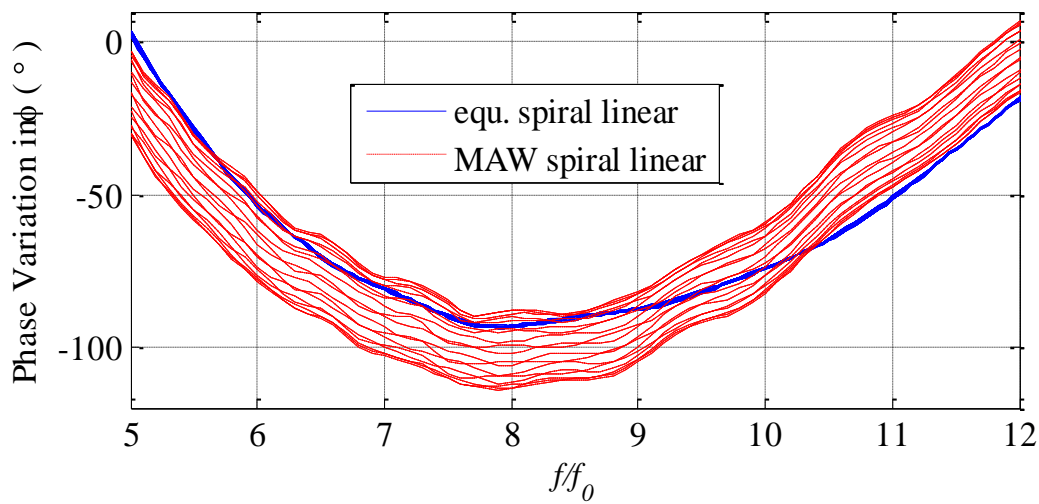


Figure 3.15: Raw AoA accuracy with delay line added on mode 1 to better track mode 2, length optimized for $8 f_0$ showing the degradation in AoA performance of a MAW spiral to a conventional spiral with no calibration technique utilized.

To evaluate the MAW's performance for AoA, first we can evaluate the conventional M2/M1 relationship. Ideally, both modes would have the same polarization, but that is not the case when a four-arm MAW is used (as shown in Figure 3.15). Unfortunately, to extract sufficient phase information to provide a tilt angle of the emitter without frequency knowledge, the resolution is limited by twice the AoA resolution because the phase between mode 1 and -1 rotates at twice the rate of the AoA, decreasing the useable bandwidth or polarization accuracy. The four-arm sinuous will do a much better job of detection of tilt angle because the two sum modes are non-dispersive over frequency although still having an ambiguity due to the two cycles of phase when the ratio is measured in ϕ unless AoA is provided. The two antennas will have equivalent performance in determining axial ratio of the emitter since no phase measurement is required. The axial ratio can be computed using Equation (10)

$$AR = \left| \frac{|V_{m1}|^2 - |V_{m-1}|^2}{|V_{m1}|^2 + |V_{m-1}|^2} \right| \quad (10)$$

where the $V_{m\pm 1}$'s are the responses of each sum mode. If on the other hand the frequency is known, then the polarization can quickly be determined using the Equations (11) and (12) once AoA determines the hemisphere of the emitter eliminating phase ambiguity. The determination of ϕ (the phase difference between the two modes at a specific angle for an arbitrary polarized emitter) is problematic without knowing the frequency and direction of the signal.

$$\phi = \angle \left(\frac{V_{m1}}{V_{m-1}} \right) \quad (11)$$

$$\phi = \angle \left(\frac{V_{m1}}{V_{m-1}} \right) \quad (12)$$

Four-arm MAW spiral mode 2 polarization, if the frequency is known, will quickly provide polarization, which can be used to improve the instantaneous AoA by finding a unique value in the lookup table within the limits wherein there is a single value mapping and the accuracy of the receiver. The single-valued mapping is limited by modal contamination, which causes 4-cycle ripple in ϕ .

The AoA spread at a single frequency is shown in Figure 3.16 for detection of broadside angle. As seen, the uncertainty in direction increases as the emitter moves off broadside. Notice that this result

does not include calibration over pattern angle for polarization, which would reduce the ripple significantly. Also, although a simple linear conversion was used to map ratio power to angle, the effects of WoW can clearly be seen in Figs. 3.16 (a) and in (b) and that WoW increases the angle uncertainty of detection.

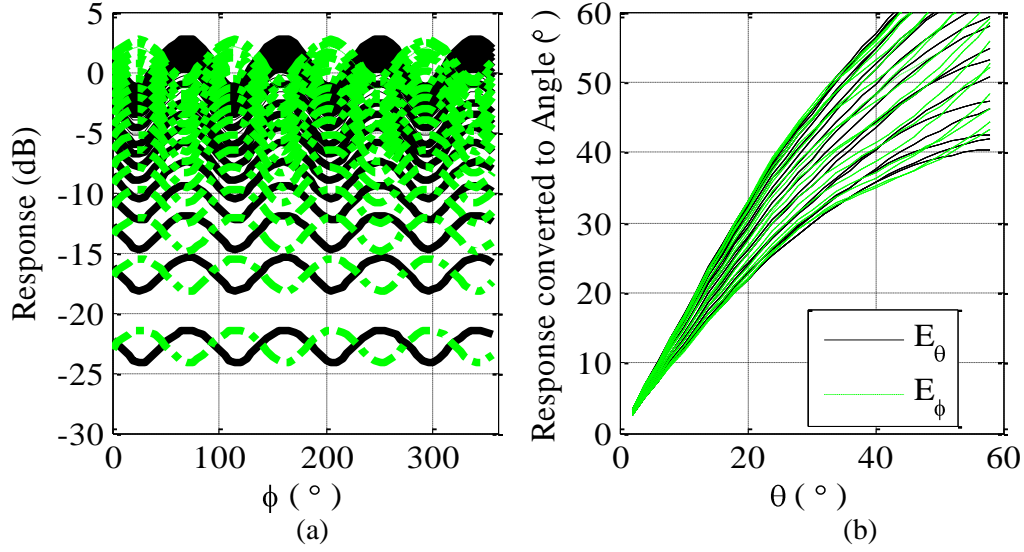


Figure 3.16: AoA performance emitter for both linear polarizations at $14 f_0$.

The MAW spiral responses like Figure 3.16 are averaged over all frequencies and the result being the mean value of the raw response to a linear emitter is shown in Figure 3.17. The linear components increase the uncertainty in the off broadside detection due to the polarization not being parallel between the modes.

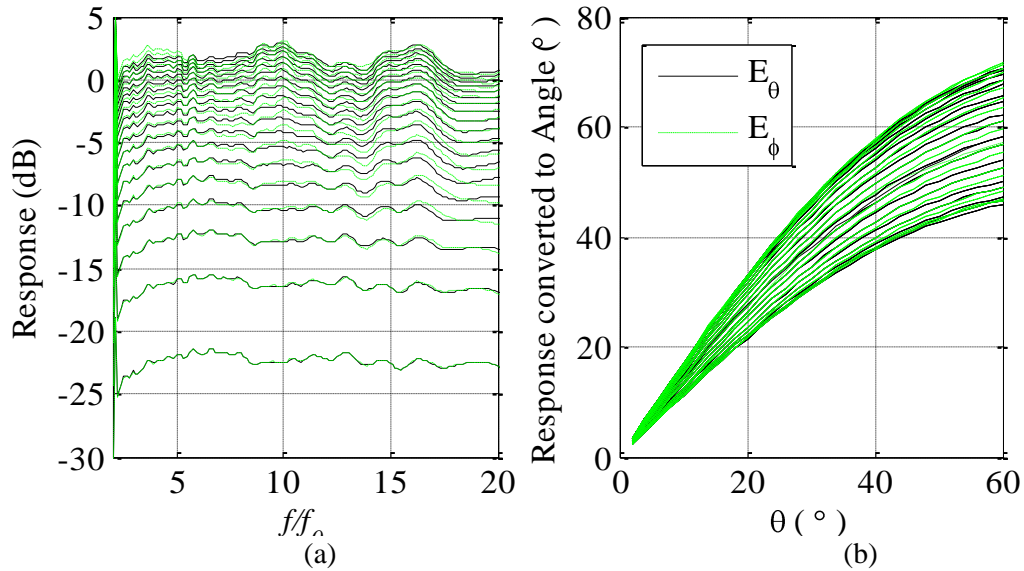


Figure 3.17: Frequency averaged AoA performance emitter linear polarized.

Note that the error in θ is approximately 1:3, which would correspond to the beamsplit term used in the literature [68]. If the measurement is then compared to the antenna pattern and polarization, this statistic can be improved, due to having two measurements (actually four with the phase) for the two field unknowns, direction and polarization, which as long as frequency is limited can have a nearly unique response to every case. Mathematical limits of this positional inversion are the orthogonality of the polarization ports and the ability to narrow the AoA. The mapping is not ensured to be purely 1:1 because of the cross coupling between the three antenna ports which will degrade the stability of the inversion search.

3.5 Phase-Center Variation

Phase centers of antennas are critical for determining location as evidenced by recent anomalies on the GPS SVN49 phased array caused by component interactions resulting in the appearance of the array to be located 152 meters in error from its true location due to the narrow band of the signal [69]. FI antennas are usually immune to this phenomenon because large available bandwidths resolve multipath issues [70]. Figure 3.18 shows the stability of the phase center of a typical MAW spiral over 20:1 bandwidth with the phase plotted rather than a physical distance.

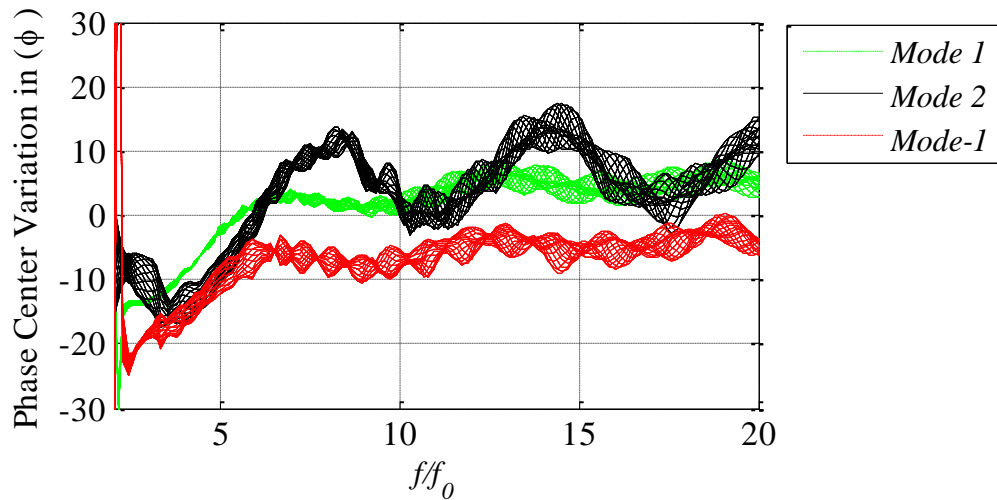


Figure 3.18: Phase center variation of a MAW antenna at $\theta = 60^\circ$, expansion factor 1.5, and modulation ratio 4.

While there is a spread of over 3° at this fixed off-axis angle, the pattern variation is small considering that there is negligible phase variation of the pattern from aligning to the spiral face. This

result demonstrates that as long as sufficient bandwidth is used the location of the antenna spatially will be known to less than the bandwidth of signal, because the phase response of the antenna varies so slowly with frequency at differing angles. To the extent, one would use this antenna as a feed, there cannot be significant phase error losses due to the extremely small astigmatism and slightly larger systematic axial defocusing between two modes of $\lambda/36$. Phase error loss as defined in [28] is the loss due to the deviation over the aperture from the average phase. This phase error loss (actually half because the two modes have opposite curvature) is less than 0.1 dB even with a shallow F/D ratio for a 120° illumination angle of 0.433.

3.6 Impedance

The impedances of the two modes are plotted in Figure 3.19. The nominal values for the resistance of the two modes correspond well to the Deschamps formula given in Equation (5). The mean resistance of the antenna for modes 1/-1 of 132.8Ω is almost the theoretical 134Ω . For mode 2, the computed mean resistance is 85.6Ω slightly less close to the theoretical 94.3Ω . The additional ripple in the impedance is caused by the quasi-self complementary nature of the MAW spiral.

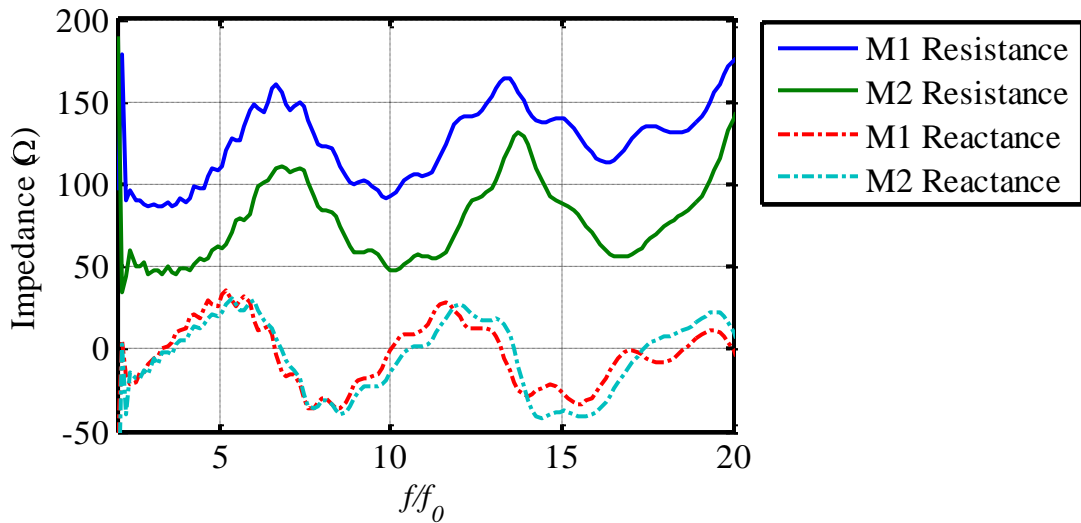


Figure 3.19: Impedance of MAW spiral (sum and difference) with modulation of 4 and expansion factor 1.5.

The modeled impedance is approximately the 2:1 expected for the mode 1 versus mode 2 from equation 5. The ripple corresponds to the reflection from the first bandstop at 1.5 rotations from the starting radius. There might be a tradeoff to reduce this ripple by having the modulation ratio increase in

magnitude, but the difficulty is to make an infinitely scalable structure finite. One obvious dilemma with this geometry is that one can achieve an FI balun that matches the impedance of both modes using a coaxial (unbalanced) feed line.

3.7 Measurement Validation

The measurements of a four-arm MAW spiral are shown to be consistent with the simulations as seen from Figures 3.1 -3. The beamformer [71] discussed in Section 3.4.2 was installed with the antenna to ensure that all mathematical processing was done correctly. In addition, because the beamformer had all modes available, mode 0/4 was measured simultaneously. Cross-polarization of mode 1 is slightly degraded due to the dielectric parameters and the differences between the fabricated prototype and modeled antenna. The results in Figure 3.20 are the measured response at 30° with all the losses and phasing differences resulting from using a COTS beamformer and commercial cables in addition to any range contamination. Only the upper band was validated during this test because of the potential for any breakdown in operation should be higher as the frequency increases.

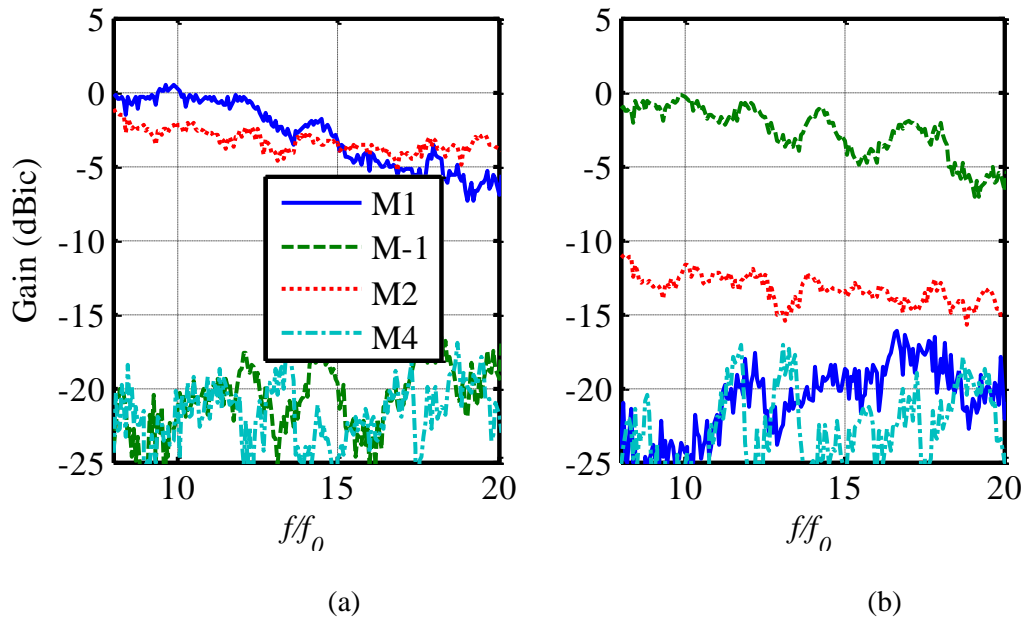


Figure 3.20: Measured average mode gains of a four-arm MAW spiral with expansion factor of 1.5 and modulation ratio of 4 at $\theta = 30^\circ$ using beamformer, demonstrating the stable existence of all three modes.

In Section 3.4.2, we presented the losses for the beamformer, a first order compensation of the loss for each of the modes to show the effective performance without the high loss beamformer is shown in Figure 3.21. While this result does not remove the modal contamination, the data in Figure 3.12 on

beamformer performance shows that the majority of contribution should be to the cross-polarization of mode 1 and -1. Another effect observed is that a potential of -10 dB beamformer contamination at the highest frequency shown is consistent with the measured results. However, based on the beamformer measurements the mode 4 contamination should be significantly lower than the cross-polarization contamination and it was not. The single arm measurements were evaluated next to determine if the beamformer was limiting cross-polarization. Please note that with the loss compensation the gain becomes more consistent across frequency. The results of combining the single arm measurements are shown in Figure 3.22, which looks very similar to Figure 3.21 of a lossless beamformer except for the reduction in cross-mode contamination that a “perfect” beamformer is expected to reduce. In the case of cross-polarization the reduction of close to 3 dB is observed above $10f_0$.

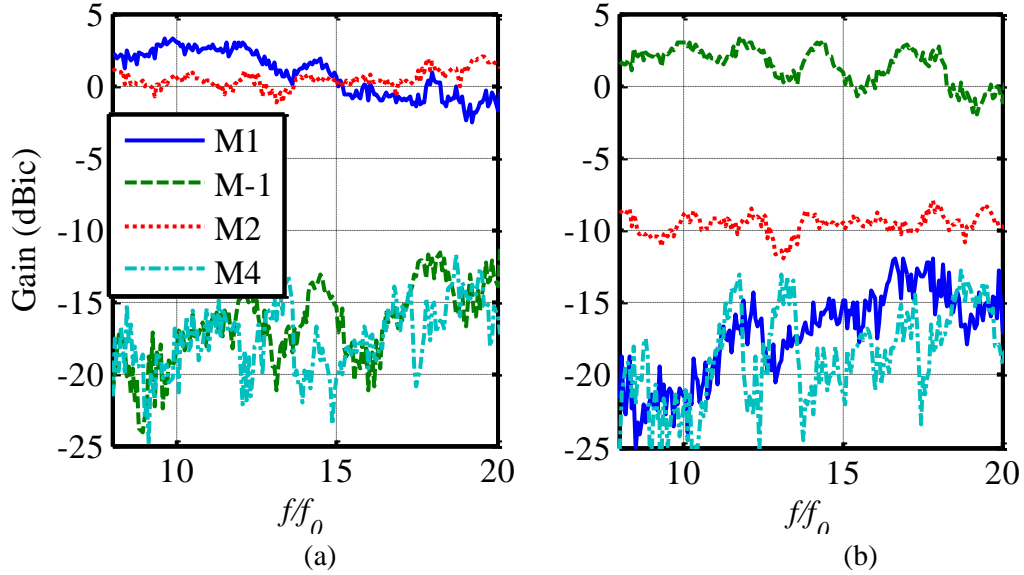


Figure 3.21: Measured average mode gains of a four-arm MAW spiral with expansion of 1.5 and modulation of 4 at $\theta = 30^\circ$, beamformer losses compensated to be more representative of the theoretical model.

The agreement for all terms, including the leakage into mode 4, is shown in the single arm rotation and summation of Figure 3.23. The results differ only slightly from the cases in Figure 3.21 and 3.22 which shows that the average contribution of the beamformer, phasing and fabrication was negligible. The results from picking a single arm and replacing all other arms with its response is also prone to range alignment inaccuracy. This was compensated based on the known range skew of 1 cm on the X axis. While the measurement itself provides an estimate of the total deviation from rotating about a

single point, as demonstrated in Figure 3.18 the physical location of a spiral phase center varies enough over frequency particularly as the antenna approaches cutoff to prevent accurate empirical determination of the range alignment from electrical measurements for values less than $\lambda/36$. This uncertainty results in a limit to compensating the measured single arm data for range errors of approximately 10° in phase. When the alignment change is small relative to the pattern structure some small variations may occur such as in the mode 2 cross-polarization between 8 and $10 f_0$. Overall the agreement between the measurement with beamformer (Figure 3.21), without (Figure 3.22), and symmetric rotation of an arm (Figure 3.23) produces very little change and the standard deviation in the measurements is similar for all three measurement method, about 0.5 dB.

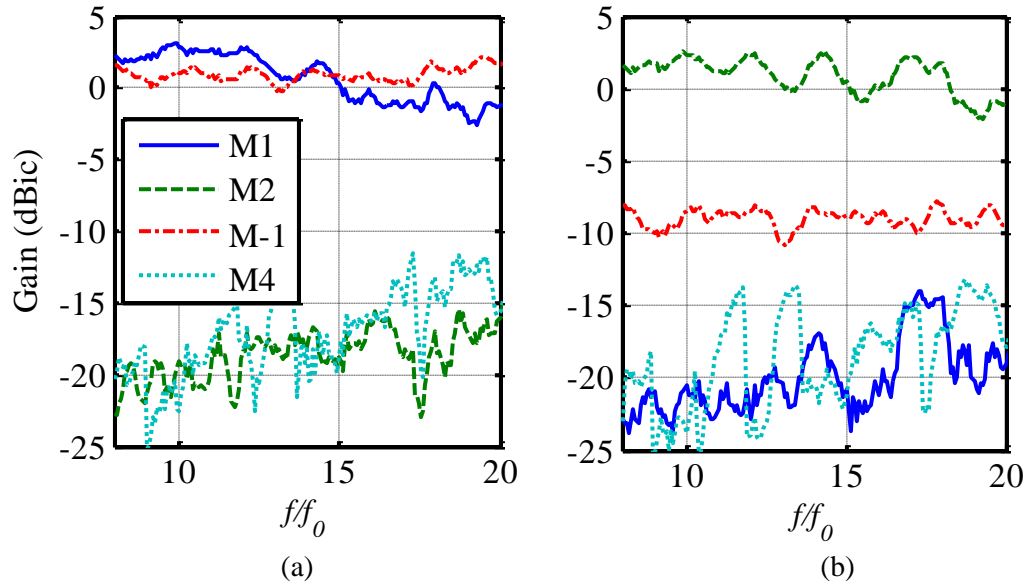


Figure 3.22: Measured average mode gains using single arm responses and summing through a mathematical beamformer.

However, the intent was to demonstrate that the four-arm MAW could provide both a sum and difference pattern and that is why we demonstrated the complete antenna performance. These results are shown in Figure 3.24. Although the measured performance has significantly more frequency ripple, the overall predictions agree, showing the mode 2 cross-polarization at -10 dB and similar cross-polarizations for modes +1 and -1 of about -13 dB, all data processed at 30° .

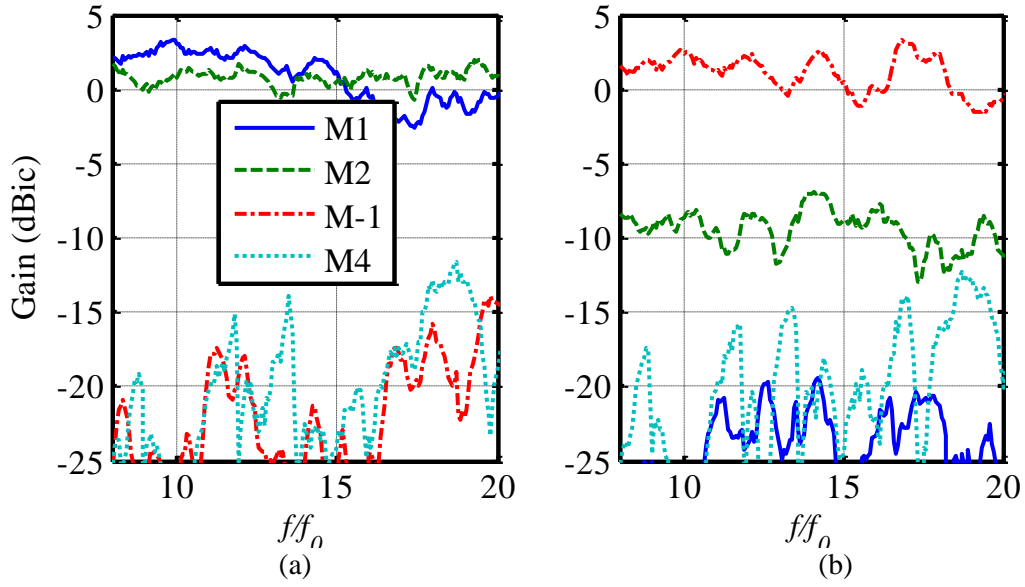


Figure 3.23: Average measured mode gains with one arm rotated to replace all other arms after removing physical misalignment of the antenna to the range.

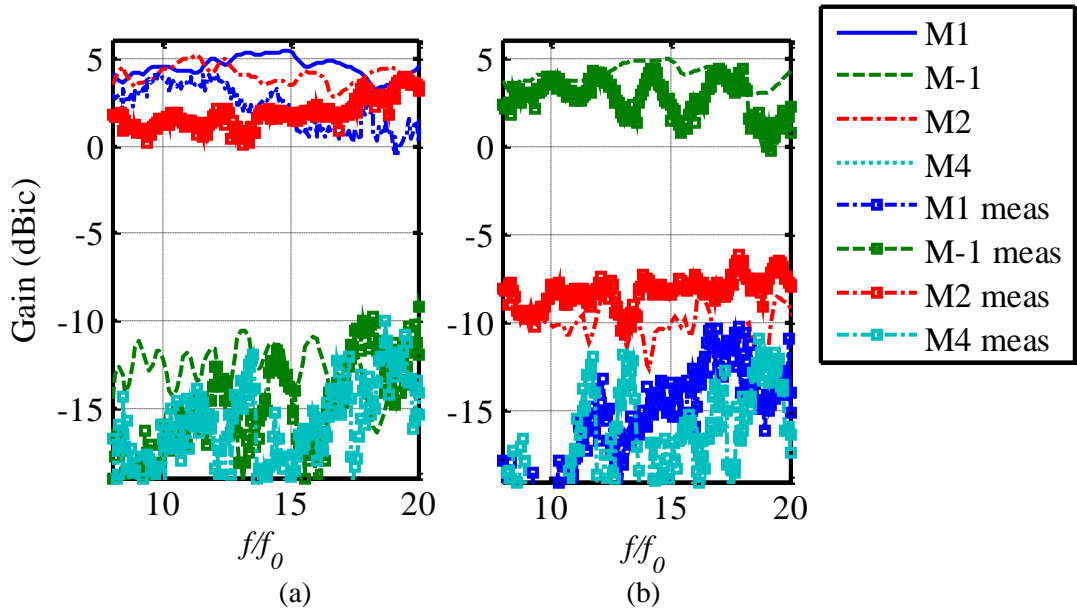


Figure 3.24: Comparison of average mode gains to the theoretical mode gains of the 5.4 cm diameter MAW spiral with an expansion factor of 1.5 and a modulation of 4 in a 2.5 cm deep cavity with 3 layer commercial absorber and a 0.5 mm substrate.

The final evaluation of the correlation of the antenna as built to the initial design was to remove all internal losses for this non optimal fabrication resulting in the overlay in Figure 3.24. The theoretical results are held static and the measured results are compensated for the beamformer losses documented in Figure 3.12 as well as the coaxial bundle loss from the manufacturer for the 23 cm run of coaxial cable, which is about 1 dB at the maximum frequency shown. There is an additional loss due to mode 4 of the

input power that could be increasing the overall loss because the term as shown in Figure 3.23 is only 15 dB down in the measurements corresponding to an additional 0.5 dB loss, whereas this effect is completely negligible in theoretical mode – more than 40 dB below prediction.

3.8 Summary

Three four-arm frequency independent antennas are compared for AoA and polarization detection. It is shown that the MAW spiral is the only element that supports both of these capabilities simultaneously in the four-arm geometry. MAW generates an acceptable difference mode with the polarization purity being limited due to the modulation, although the AoA performance is degraded when compared to an equiangular four-arm spiral. It is seen that the polarization detection without frequency detection is limited by the ability to compensate for the dispersion between the two sum modes, a problem not found in a sinuous antenna. The sinuous still has an embedded phase term to derive polarization tilt angle, and it is dependent on direction of the signal, and only can be derived using AoA information. For the sinuous antenna, this information is not available from a single four-arm alone. A completely integrated antenna was measured to show that the three modes are not an artifact of any mathematical processing and that no significant power was being reflected or absorbed into the mode 0/4 port.

CHAPTER 4

NON-SELF-COMPLEMENTARY DESIGN INVESTIGATION

This chapter provides a more detailed investigation into the performance of the bandstop, cavity and dielectric, with the particular emphasis on the control of the four-arm MAW spiral difference mode of the antenna. In this case, as discussed in Chapter 3, the mode 2 and mode -2 are not separable by the beamformer. The remaining area that merits further investigation is the element geometry. If the MAW spiral element could improve its rejection of mode -2 then the AoA accuracy will improve because the polarization of the sum and difference modes will converge. In the Equation (13), there is a small change made to the exponent by replacing 4 for a four-arm antenna with τ to increase the flexibility of the geometry choices. This change is not arbitrary and is tied to an observed problem with modulations providing polarization control from Figure 3.7. An additional parameter is needed because the existing ones do not change the cross-polarization for mode 2.

$$r = r_0 e^{\alpha\phi} \approx r_0 EXP^{((\phi + \text{sgn}(\sin\tau\phi))\phi_0)/(2\tau)} \quad (13)$$

where τ = period of modulation, ϕ_0 = offset angle of modulation

4.1 Non-Self-Complementary MAW Spirals

A new MAW spiral configuration is proposed for improved control of the mode 2 performance. This new configuration is accomplished by tuning the modulation period, at the expense of the self-complementary geometry as mathematically described in Equation (13). This new topology can result in degraded impedance and reverse mode (-1) operation. The new non-self-complementary topology is proposed because the variation of modulation ratio and expansion rate, the parameters normally used to

control mode -1 operation, showed little change in mode 2 polarization as shown in Figure 3.7. This insensitivity indicates that mode 2 performance might be controlled independent of mode -1. The most important design feature investigated in this chapter is modulation period (τ), which is a method to control mode 2 polarization outside the radiation region for a four-arm MAW spiral. The dielectric and cavity backing degradation effects on the pattern for a fully realized antenna are also evaluated.

The geometry of a MAW spiral is unlike a conventional spiral, which inherently imposes the polarization of the arm wrap and improves polarization by lowering the expansion factor. By allowing the MAW spiral definition to include geometries that are not rigidly self complementary, perhaps the polarization behavior of conventional spirals can be better approached. The reason for improving polarization consistency between mode 1 and 2 is to decrease the uncertainty of analog AoA where the sum and difference ideally have the same polarization.

While it is possible in theory to solve for the AoA uniquely if the polarization is known, the solution stability increases as the polarizations of mode 1 and 2 become the same because less error accumulates in the cross term. This result is obtained by inspection of the 3×3 matrix generated by the three modes of a four-arm MAW spiral converting to AoA and polarization. The first and second equations reduce to the coupling between mode 1, 2, and cross-product, ideally 1 and 0, respectively. The third equation is the response of mode -1, which is ideally orthogonal to the other two modes yielding a matrix that approaches diagonal. This matrix is stable for all conditions other than the mode 1 being orthogonal to the emitter resulting in no response on modes 1 and 2 (in the ideal case) for AoA.

Layouts of four different four-arm equiangular MAW spirals are shown in Figure 4.1, with increasing modulation frequency from (a) to (d). For this first evaluation, we kept all parameters constant except the period. An expansion factor of 1.5 and a modulation ratio of 4 were chosen as stable variables that would not be impacted by manufacturing limitations. Fig 4.1(c) is the self complementary case used in Chapter 3 and is only provided for reference to the other proposed geometries.

The MAW geometries chosen should have similar polarization in mode ± 1 if τ is chosen not to affect the performance of the normal operation. For the MAW spiral shown in Figure 4.1 (c) $\tau = 4$,

meaning that polarization for mode 2, while predominantly controlled by the antenna wrap, is also contaminated by the presence of resonance bandstops in the mode 2 radiation region. Bandstops in this location result in collocated mode ± 2 , thus not improving rejection of either polarization. The other geometries (a, b and d) represent potential improvement for some performance metric. While use of self-complementary structures is the norm when developing a frequency independent antenna, it is typically done in the initial design to ensure the impedance of the antenna will be known to the first order and will be stable over frequency. For the geometries in Figure 4.1, a question was whether a significant impedance variation was created by the design not being self-complementary.

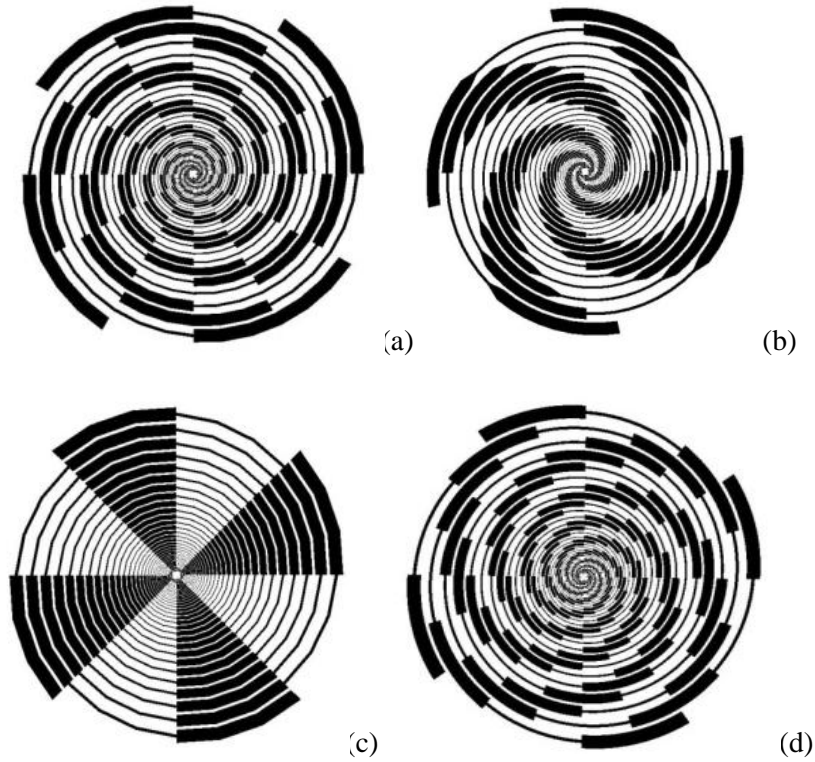


Figure 4.1: Layout of four-arm planar MAW spirals with expansion and modulation of: 1.5 and 4, τ equals (a), 3 (b), 3.5 (c), 4 and (d) 5.

The actual τ was chosen in each case to highlight a possible performance capability.

- $\tau = 3$ was picked to examine the behavior of mode -1 and 2 when they should have no dispersion. This situation is because the bandstop reflects the current for mode -1 halfway between modes 1 and 2.
- $\tau = 3.5$ was chosen to examine the behavior of mode 2 when the period is not an integer.

- $\tau = 5$ was selected to examine the behavior when the bandstop should not be part of the circuit except for mode -1.

Figures 4.2 and 4.3 show the relative impedance of the four designs. Note that the mode 2 impedance is significantly degraded if $\tau < 4$. The mode 2 impedance is almost unchanged for $\tau > 4$. Dielectric effects are included in these results, specifically an 0.5mm thickness Rogers Duroid 5870, $\epsilon_r=2.33$ with loss tangent 0.0012. Effective loading was slightly less than 10% of the free space delay of the transmission line. A cavity was incorporated as well to make the results similar to an antenna that would be fully assembled, although the antenna was not embedded in a ground plane. Modes -1 and 1 are shown based on calculations from a single arm impedance with all cross-coupling. This approach will always lead to an identical impedance for the modes. The assumption is valid as long as all materials are isotropic. It is possible that the two modes will not be identical if the direction of propagation in the material is affected differently by the polarization.

The results of the mode 2 impedance calculation show fairly unstable impedance until $\tau > 3.5$. For the $\tau = 5$ the impedance is very similar to the nominal case which appeared to be a good compromise for building a well behaved MAW spiral. If one considers the two periodicity options, the case of having $\tau < 4$ places the bandstop before the radiation region. This approach seems problematic, as the expectation of the transmission line model is that the currents would reflect back into the feed instead of radiating mode 2. Having $\tau < 4$ may result in a standing wave transmission line with a fairly high Q due to the currents being reflected several times between the bandstop region for mode 2 and the feed point, before either being absorbed or radiated depending on the bandstop efficiency.

4.2 Radiation Patterns

The less obvious impact of varying τ on the radiation patterns is to the mode ± 1 operation. Since the radiation region for these modes is still inside the bandstop region as long as $\tau > 2$, the geometry that is not self complementary should not be disruptive to these patterns from the appearance of the input impedance. One would expect that the radiation performance should resemble the impedance, if one is smooth over frequency then the other should be as well. On the other hand, if the modulation period is

increased from 4, it will be expected to become less effective. Upon reaching $\tau = 6$ modulation is useless since the currents will then pass through the radiation region for mode 3 before being reflected into the mode ± 1 radiation region. The investigation of improvement for mode 2 polarization without losing performance of mode ± 1 focused on bandstops being $3 < \tau < 6$. As discussed above 3 and 6 are poor choices for mode -1 performance.

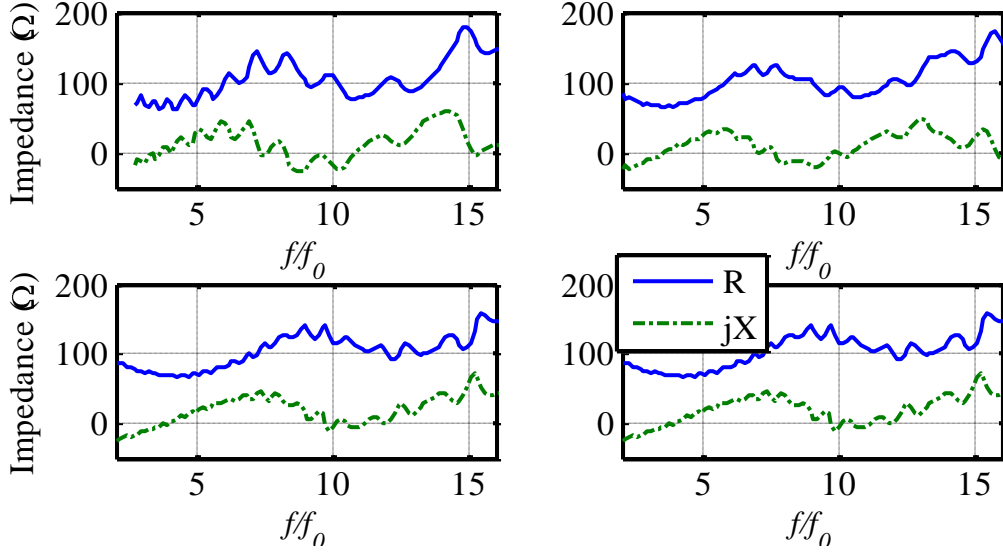


Figure 4.2: $M = \pm 1$ Impedance of planar four-arm MAW spirals (a) in the top left hand corner, $\tau = 3$, (b) upper right hand corner, $\tau = 3.5$, (c) lower left hand corner, $\tau = 4$, and (d) lower right hand corner, $\tau = 5$.

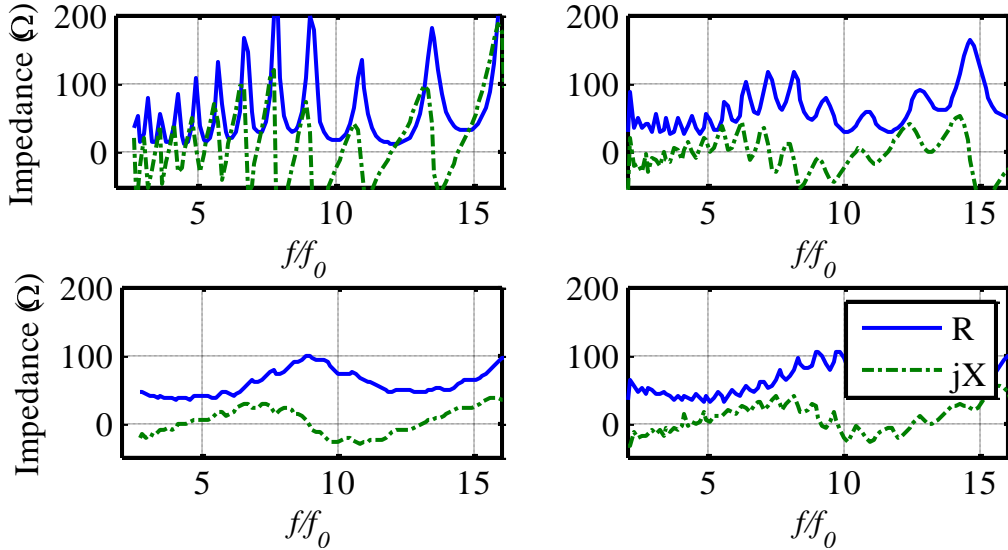


Figure 4.3: $M = 2$ Impedance of planar four-arm MAW spirals. (a) in the top left hand corner, $\tau = 3$, (b) upper right hand corner, $\tau = 3.5$, (c) lower left hand corner, $\tau = 4$, and (d) lower right hand corner, $\tau = 5$.

The second more computationally intensive task is to determine if dielectric loading will

significantly shift the interaction of the bandstops and change the bandstop location relative to the radiation ring. Typically, this effect should be minimized because if the resonant radiation ring is not collocated with the transmission line ring of the same mode the polarization is degraded. The design kept the dielectric loading to $<10\%$ (based on the difference in delay between the model in free space and the one on a dielectric) so that the free space radiation region coincides closely with the radiation region in the effective dielectric of the transmission line [47]. This requirement will impose a maximum dielectric thickness limit of $\lambda_{min}/25$. While increasing the loading may improve the bandstop effectiveness for mode 2, it would definitely degrade polarization purity on modes ± 1 .

Figure 4.4 shows how significantly all modes are affected by the modulation, resulting in an anti-resonance in the pattern every time the frequency moves to the next wrap size. On the other hand the cross-polarization is excellent for mode 1 and 2. The plots include an overlay of the 72 cuts in ϕ to show the relative spread as the antenna is mathematically spun and swept in frequency.

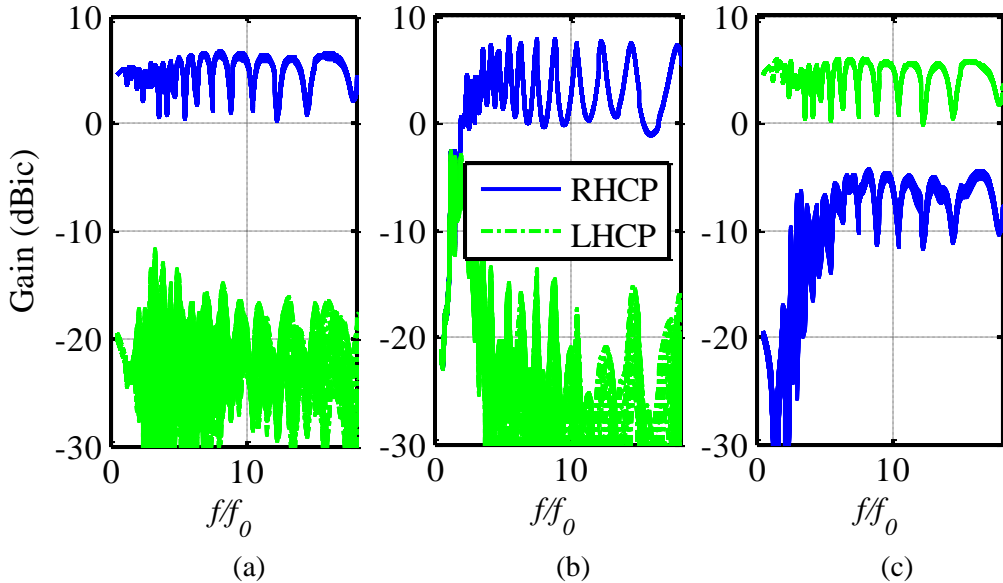


Figure 4.4: Pattern at $\theta = 30^\circ$ of planar four-arm MAW spiral $\tau = 3$. Plot designation is Mode 1 (a), Mode 2 (b), Mode -1 (c), free space.

Looking at this example with a reasonably thin dielectric and low expansion factor, the best performing design should be near $\tau = 3.5$ based on a compromised between ripple and polarization, although there is an additional minimum between $4 < \tau < 5$ that has less frequency ripple. Looking at the case in Figure 4.5 ($\tau = 3.5$), the performance could be further improved with a higher modulation ratio

(possibly 8) to improve mode -1. Although mode 2 had a lower cross-polarization term in the free-space simulation with a 3.5 period than the period 5 response in Figure 4.7, both appeared to be improvements with respect to the period 4 geometry in Figure 4.6.

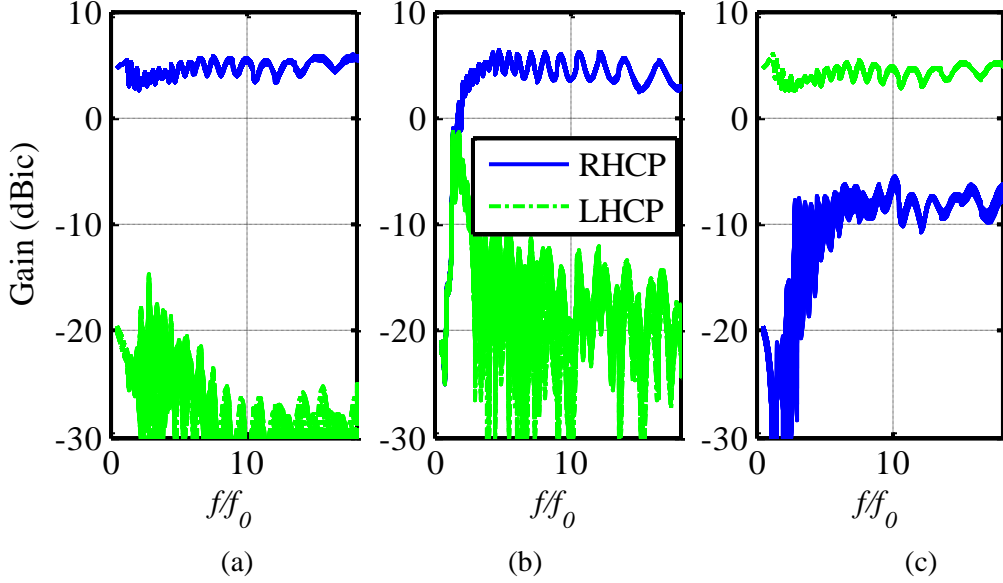


Figure 4.5: Pattern at $\theta = 30^\circ$ of planar four-arm MAW spiral $\tau = 3.5$. Plot designation is Mode 1 (a), Mode 2 (b), Mode -1 (c), free space.

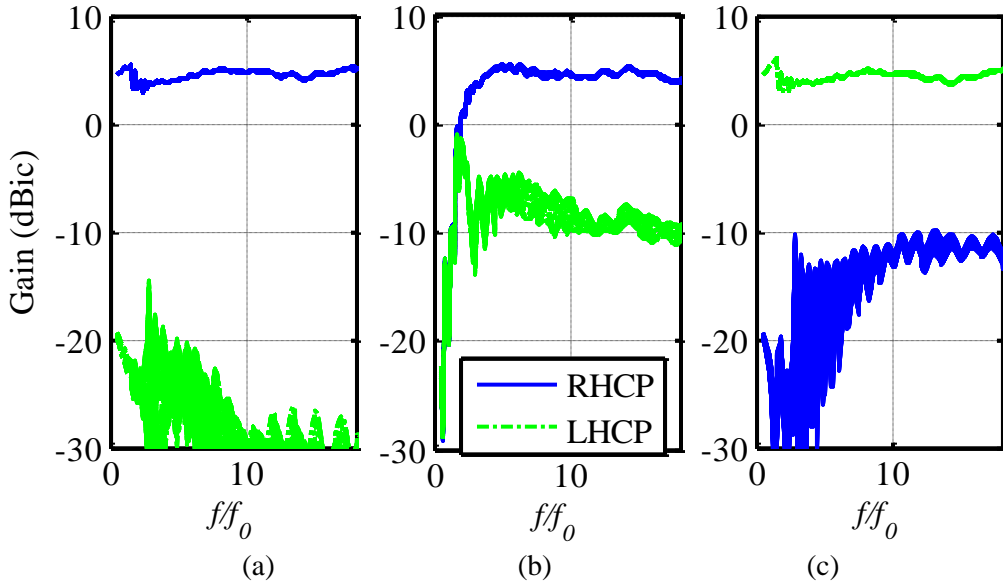


Figure 4.6: Pattern at $\theta = 30^\circ$ of planar four-arm MAW spiral $\tau = 4$. Plot designation is Mode 1 (a), Mode 2 (b), Mode -1 (c), free space.

The beamformer has no way to reject mode -2 while receiving mode 2 because the arm phasing is identical. Only the geometry can be used to improve rejection of the undesired mode/polarization.

Knowing that the individual bandstops are only moderately coupled to the other arms of the MAW spiral, changing the resonant bandstop location to some radius other than the radiation region provides better polarization control. This is because the bandstop will then be working as a transmission line element without radiating. Having the bandstop on either side of the mode 2 radiation region could be acceptable, however, better impedance performance has been modeled with the bandstop outside the mode 2 region. Note that mode ± 1 impedance is unaffected.

The significant change from the geometries of the MAW spiral previously investigated is the introduction of a geometry that is not self-complementary. While the metal to gap ratio still averages 50%, the metal structure is not the image of the gap. Actually changing the ratio of metal to gap is benign from the theory as described in Chapter 2. However, in the case of $\tau \neq 4$, the bandstop geometry has no clearly defined low and high impedance sections. This impedance characteristic will cause impedance instability.

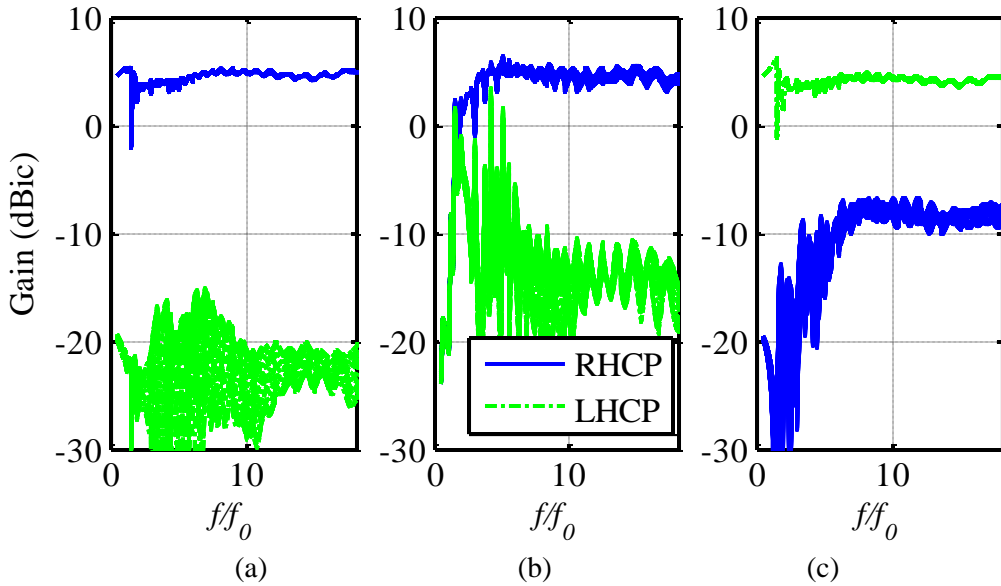


Figure 4.7: Pattern at $\theta = 30^\circ$ of planar four-arm MAW spiral $\tau = 5$. Plot designation is Mode 1 (a), Mode 2 (b), Mode -1 (c), free space.

From above, the modulation frequency of the four-arm MAW spiral needs to be $3.5 < \tau < 5$. If the frequency response does not need to be flat, it is possible that the geometries with periods less than 4 have better polarization match for mode 1 and 2 but elevated mode -1 cross-polarization. The choice is whether matched polarization for AOA or orthogonal polarization for polarimetry is most desired.

For the MAW spiral, the delay and hence dispersion between mode 1 and 2 is the same as for a spiral of the same growth rate regardless of τ or modulation ratio because the bandstop is not part of pattern delay for these modes. Figure 4.8 shows that the dispersion for the reverse mode -1 relative to 2 is controlled by τ , with the dispersion increasing in direct proportion to τ . While no obvious application arises from the $\tau = 3$ case, the result is a true FI monopulse antenna for linear polarization. The delay between modes 2 and -1 differs smoothly but is non-linear over frequency. While a sinuous antenna will have the same dispersion in both positive and negative modes, the dispersion is not monotonic over frequency as with spirals, (equiangular or MAW). Confirmation that the additional delay arising from bandstops is proportional to τ proves that understanding single arm operation is an excellent way to predict the MAW antenna properties.

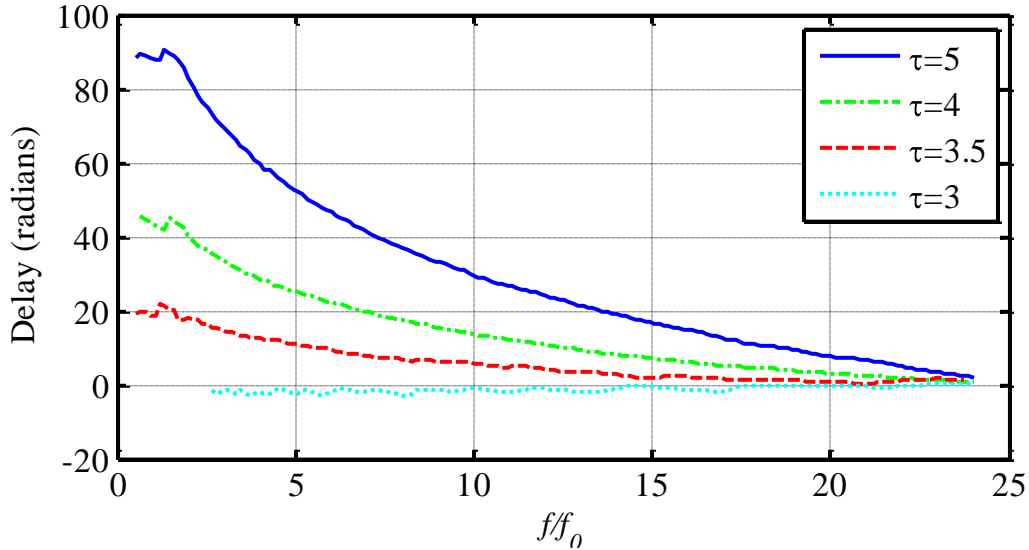


Figure 4.8: Modal delay between mode 2 and -1 of planar four-arm MAW spirals for various τ .

4.3 Full Model Geometry with Cavity and Dielectric

To be confident of the design selection of the antenna, the performance must be accurately predicted by the modeling tools. To make the design representative of the “as built” antenna while keeping the computational overhead small, most of the performance was validated using free space. Next, the acceptable designs were taken through the additional step of processing with multi-layer Green’s function to introduce dielectric into the antenna. Solving the multi-layer Green’s function increased the computational load approximately 10 times in observed computation time. The problem took 301 CPU

hours with the dielectric, versus 31.68 hours for one in free space. The problem size was 2 GB in memory and used 4 Intel Xeons on a 3.2 GHz clock in a 64 bit operating system. The effect is due entirely to the introduction of dielectric. The other methods available within the FEKO solver were predicted to be less efficient based on the documentation of the application [72].

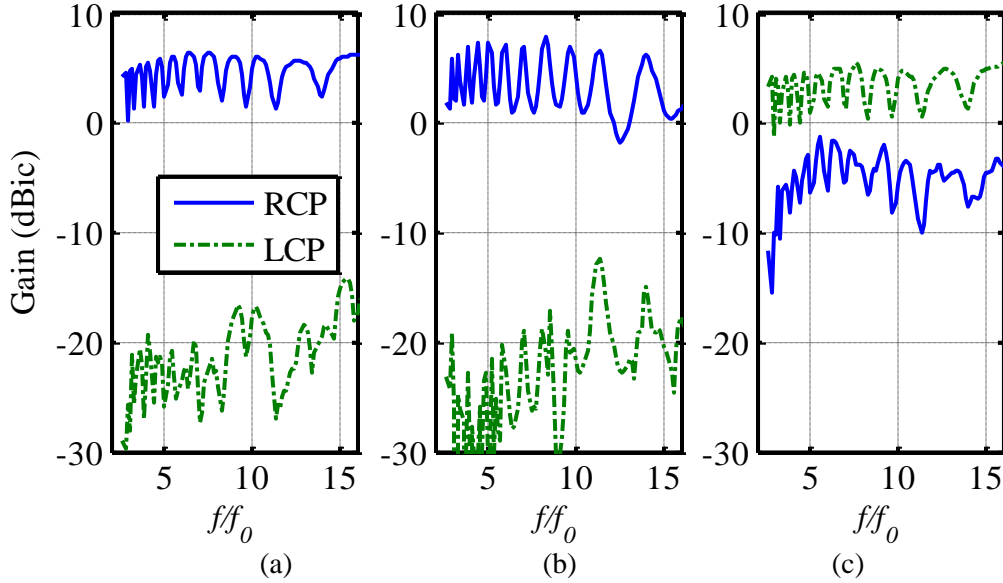


Figure 4.9: Average pattern at $\theta = 30^\circ$ of planar four-arm MAW spiral, $\tau = 3$, plot designation is mode 1 (a), mode 2 (b), mode -1 (c), left to right.

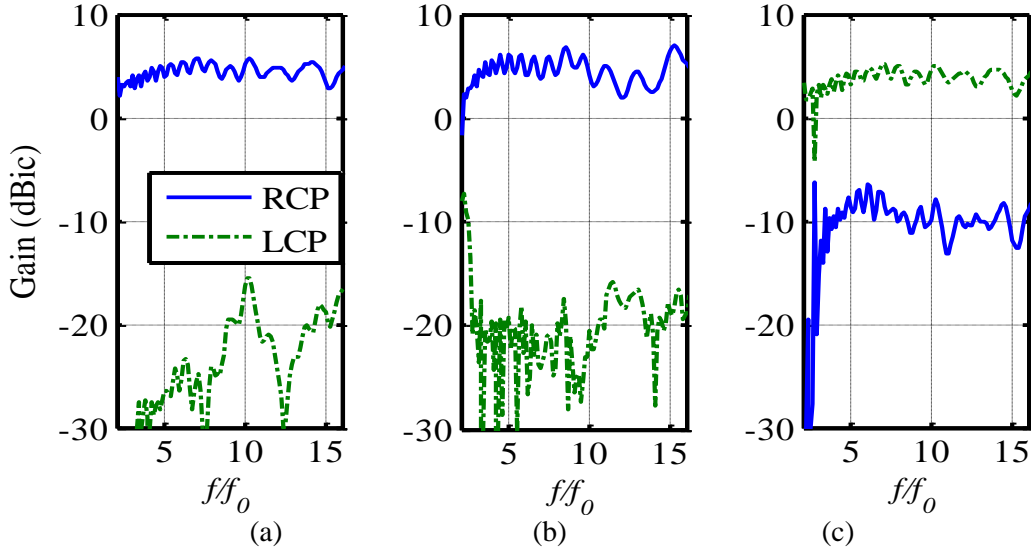


Figure 4.10: Average pattern at $\theta = 30^\circ$ of planar four-arm MAW spiral, $\tau = 3.5$, plot designation is mode 1 (a), mode 2 (b), mode -1 (c), left to right.

Previous work had shown that accurate prediction of a specific antenna's performance requires inclusion of the dielectric, because the loading of the transmission line can have significant change on the propagation delay to the radiation region. A cavity slightly larger than the antenna was used in the model

and a second layer of dielectric with absorptive properties was added behind the cavity to reduce the backlobe. Results for all geometries are shown in Figures 4.9-12. The element chosen for comparing free space to a realistic “as built” geometry was the self-complementary example from Figure 4.1 (c).

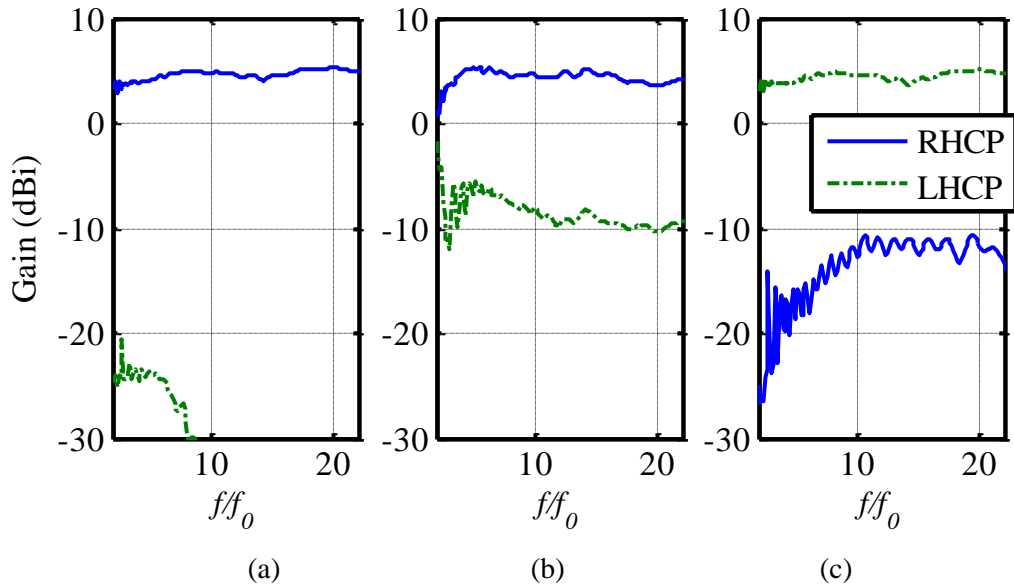


Figure 4.11: Average pattern at $\theta = 30^\circ$ of planar four-arm MAW spiral, $\tau = 4$, plot designation is mode 1 (a), mode 2 (b), mode -1 (c), left to right.

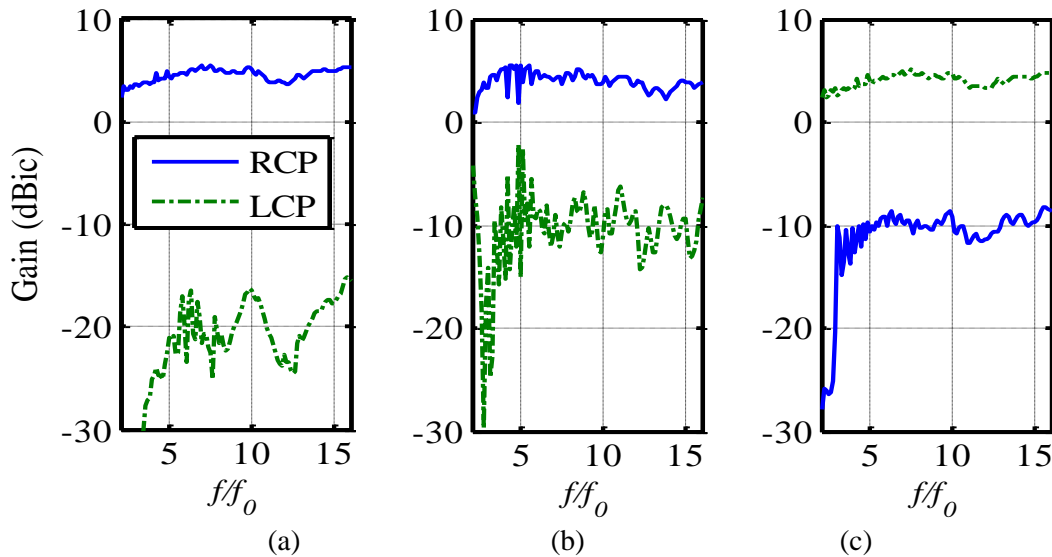


Figure 4.12: Average pattern at $\theta = 30^\circ$ of planar four-arm MAW spiral, $\tau = 5$, plot designation is mode 1 (a), mode 2 (b), mode -1 (c), left to right.

Practical experience has shown that except for cases where the absorber is too close to the spiral or has poor absorption, the antenna responds similarly to cavity absorber as free space. The absorber is usually multi-layered to reduce depth, and adds further computational demands. Figures 4.13 and 4.14 show the differences between free space, cavity with a PML treatment, and absorber based on Emerson &

Cuming LS 20 [73]. The absorption property was simulated as conductivity (approximately 0.37 S/m) which tracks better over large frequency ranges than using a constant dielectric loss tangent.

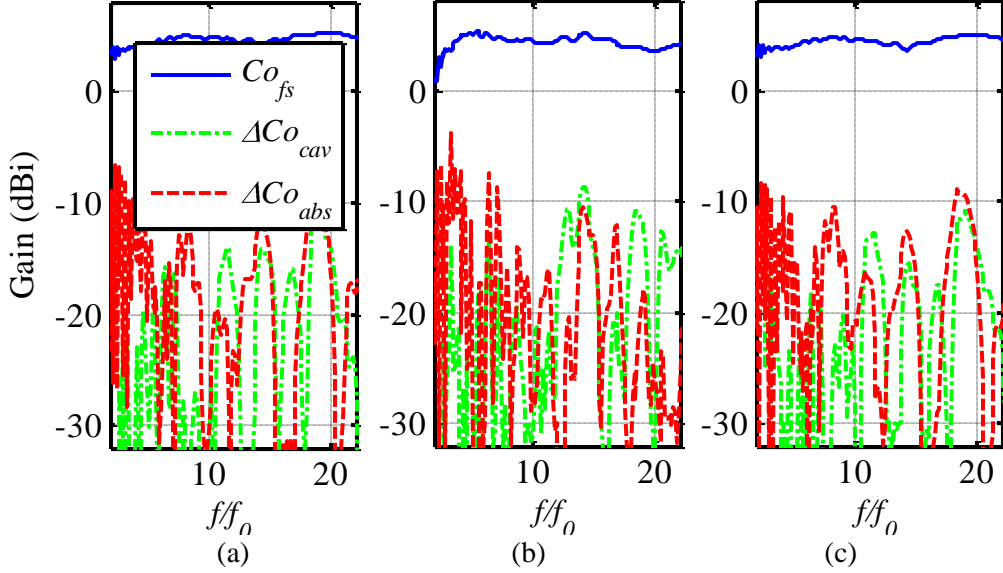


Figure 4.13: Cavity performance (co-polarization), (a) mode 1, (b) mode 2, (c) mode -1.

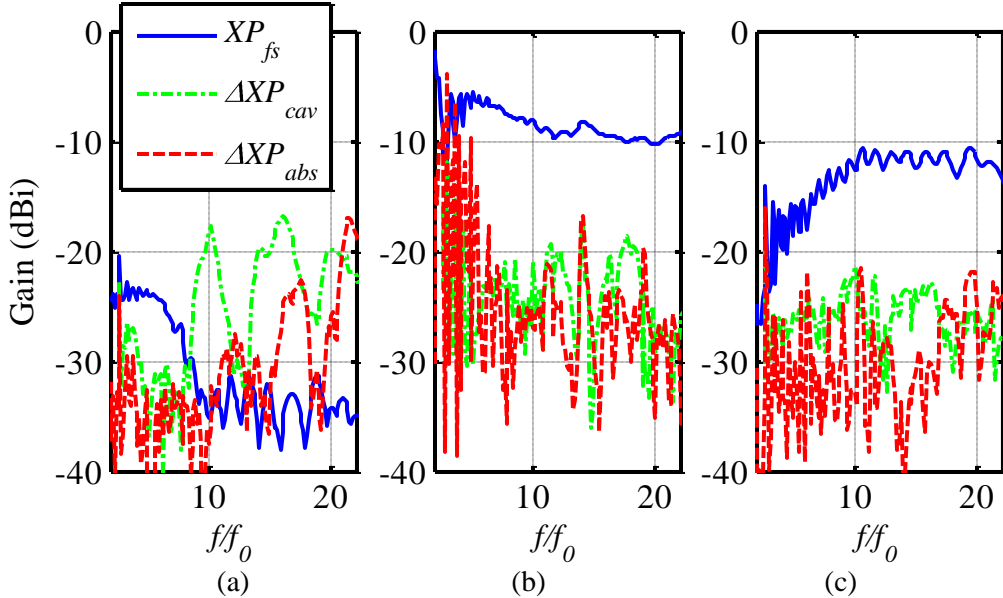


Figure 4.14: Cavity performance (cross-polarization), $\theta = 30^\circ$ (a) mode 1, (b) mode 2, (c) mode -1 for self-complementary case.

To better show the impact of cavity and absorber simulations, the difference in the residual field was plotted relative to nominal field from the baseline free space model. Shown this way, it is apparent that for all cases except mode 1 cross-polarization, the changes in the performance were typically 10 dB or more below the measured parameter above cutoff frequency. Obviously, the mode 1 cross-polarization

is sensitive because the antenna has no significant component in free space. Thus, we claim that for the observed phenomenon from the dielectric, cavity and absorber/PML that the results were very similar to the simpler free space model that required $1/10^{\text{th}}$ the computational time. A design with a thin low dielectric material was used because previous measurements in Chapter 2 at a substrate thickness of 0.82 mm and $\epsilon_r=4.5$ had shown significant performance degradation. The selected material has a thickness of 0.5 mm and $\epsilon_r=2.33$ ($< \lambda_{\text{eff}}/50$ at $f=10f_0$) over twice the frequency range of the previous material described in Chapter 2. The change was expected to improve the observed performance in both the model predictions based on the measurements from the electrically thicker dielectric. The result of the absorber simulation was that not only would conventional absorber work quite well for this design, but that the pattern changes due to the cavity walls were more significant than the material backing the antenna whether the material was absorber or PML.

While the beamformer was not included in the MoM solution of the antenna, the simulated results easily allow implementation of a non-ideal beamformer as necessary using the method of superposition of sources. This technique can even include the mismatch if necessary. However, validation of the designs included in this paper was done by measurement in order to show good performance was achieved with typical components and no unusual tolerances were needed to match modeled results. The beamformer is relied on for low axial ratio in the physical antenna because the MAW spiral antenna element does not reject either polarization as thoroughly as an equiangular spiral. The overall polarization degradation was about 2 dB. While this is not significant to efficiency, it is very important to AOA [74, 75]. Figure 4.15 shows the correlation between error and polarization for a linear emitter on a circularly polarized sensor.

Some improvement in performance of the sensor can be provided by compensating the antenna for the estimated polarization using a calibration table. However, the curve in Figure 4.15 is the result of comparing the raw sum to difference patterns, with the error resulting from the solid angle estimated by the polarization orthogonality (cross-product of the pattern of the two modes). Similar and more detailed analysis can be performed on local pattern variations such as WoW, which corresponds directly to an error in pointing, and phase, which causes clocking in the AOA. If the polarization of the emitter has been

sensed, then the results improve dramatically due to the extraction of the transcendental relationship between the modes. This is due to the relative voltage presented at the three ports is a function of all three terms (θ , ϕ and polarization).

The four-arm MAW spiral antenna provides complete ambiguity free resolution of received polarization and direction of a signal to the limits of the calibration of the antenna. The MAW spiral antenna geometry also provides a limited range of control for the polarization of the three modes. The polarization of the reverse mode of operation is provided by both the growth rate and modulation, with the difference mode provided by the period of the modulation. While this antenna will not have the same purity for polarization as two dedicated antennas or a higher arm count frequency independent antenna, it will provide the solution to measuring emitter direction and polarization with minimum complexity.

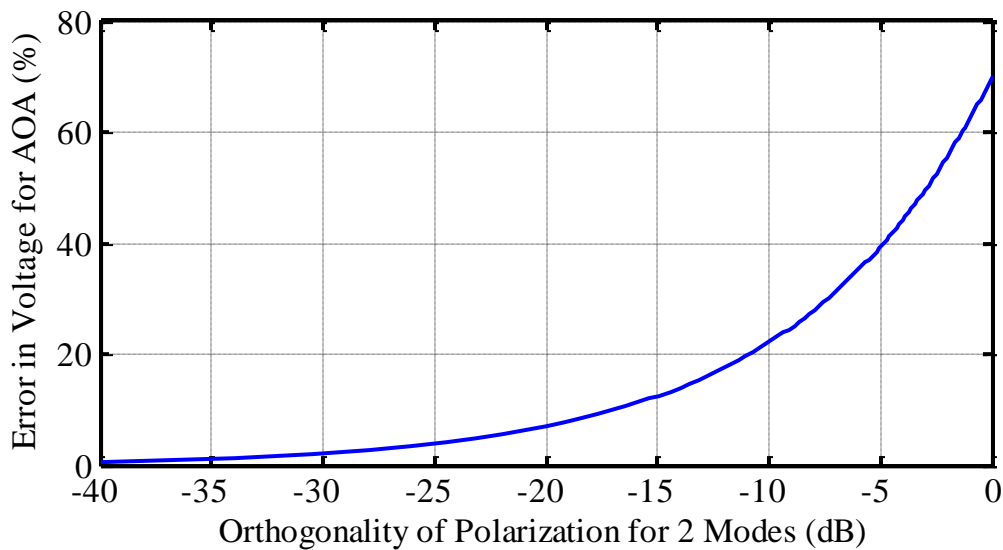


Figure 4.15: Effective error for uncompensated AOA of antenna from how orthogonal the polarization is between sum and difference mode (0 being the desired magnitude of the cross-product).

CHAPTER 5

MULTI-ARM CAPABILITIES

Although the research to this point had been on four-arm MAW spirals, the other arm counts were also investigated to determine if they have useful pattern properties. One condition of note was that as the arm count increases the mode that the beamformer controlled and the next mode was shown to have poor isolation even with adjustments to the period. For example, if the antenna had six arms, it should have five useful modes. These modes would be expected to be ± 1 , ± 2 and 3, but not -3. What was typically found was that the performance of the highest mode would be degraded, primarily by the next closest mode. This behavior was because the opposite polarized mode had the same arm phasing and radiated at about the same circumference. In the six arm case both 3 and -3 have a 180° flip between arms and had to rely on the element alone for polarization control.

For odd arm counts the control was even weaker because the next higher mode had the same phasing and was co-polarized to the spiral wrap. Thus, the mode could only be eliminated by the bandstops, which as the arm count increased had to have a very small ring to be effective between the two adjacent modes. The simplest example of this situation would be the three-arm MAW. For a conventional equiangular spiral the modes are 1 and 2, for the MAW the desired modes are -1 and 1, but to get a significant mode rejection the bandstop period needed to be increased, moving it further away from the radiation region to be effective. This approach becomes less effective when arm count is higher because the separation in radius between the bandstop and radiation region decreases. The other significant observation was that the lower modes were controlled much better by the MAW spiral when the arm

count increased, providing performance similar to the best sinuous without the additional difficulty of matching that the sinuous has due to arm interactions. Figure 5.1 shows the self-complementary versions of arm counts 5 to 8 with 8:1 modulation ratio and a slight increase in the growth rate from 1.5 for the five arm to 1.75 for the eight arm.

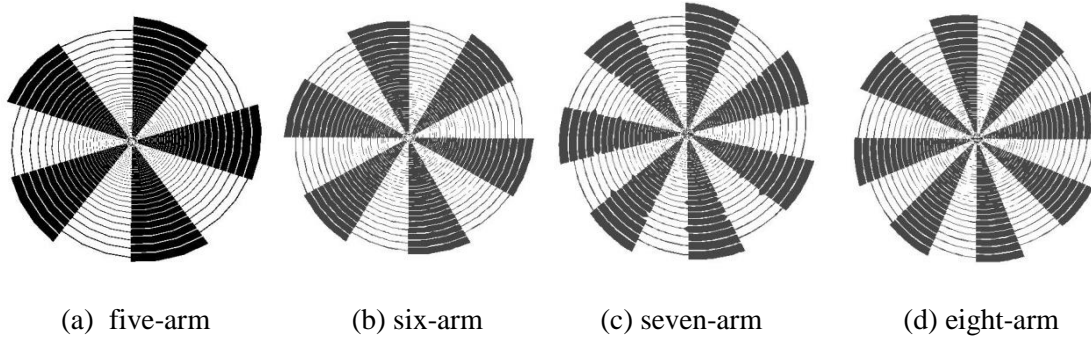


Figure 5.1: Various arm count geometries.

Although a physical prototype was not developed for this chapter, excellent agreement between models and measurements shown in the previous chapter strongly suggests that the findings described herein are valid. The application for these different arm counts would be for new performance requirements, for example, a MAW spiral with more than four arms provides matched polarization response for performing AoA as recommended in most signal processing techniques, with independent orthogonal polarization detection. With each additional arm above the measurement requirements, the element provides improved capability to control the pattern of the antenna.

5.1 Theory

Most of the underlying theory of the MAW spiral at an individual arm level has been addressed in the previous chapters. In this chapter, the majority of the expansion conceptually is to break the antenna pattern into modes consistent with the processing requirements to observe how well controlled the modes are as well as whether there are any significant uncontrolled modes due to the bandstops not being sufficiently efficient. The particular scope of the theory clarified here is that if the MAW spiral is working near optimum, the modes available for use are one less than the total arms. Performance of all modes except the highest are controlled well using the normal parameters of modulation ratio and growth rate. The highest mode can sometimes have its polarization improved by changing the period of the

modulation, but this decision must be balanced against the resulting modal impedance problem.

If the single arms are modulated independent of the frequency consistent with the arm count then modes can be lost completely because the MAW spiral will reflect the power in the radiation region away from the feed point. This type of behavior was demonstrated in the previous chapter when the modulation frequency was decreased below 4. The bandstop can also create modal contamination by allowing the antenna to radiate two modes efficiently if the frequency of the bandstops is too high, again causing the antenna to lose control of modes. For example if the five arm spiral is modulated at a frequency of 6 then mode -3 and mode 2 will both radiate with the same beamformer, as well as mode -2 and 3 because the modes all radiate inside the resonant circumference of the bandstop.

5.1.1 Beamformer

The beamformer of the 4, 6 and 8 arm MAW spiral can be realized with hybrids and needs to be fully populated to allow simultaneous detections of all modes. For a generic, ultra-wideband beamformer, all the data processing needs to be done digitally, so the performance of the single arm dominates the power transfer because the first stage of the beamformer would be set by the power transfer from the arm to the amplifier. Figure 5.2 shows the mismatch of each of the geometries from three to eight arms. Although there is a high degree of coupling between the arms, once the power has been transferred to the amplifier the arms are highly isolated as they were with the coaxial feed cluster. If the amplifier were flipped for transmission mode, the pattern and mismatch loss results would be the same although the MAW spiral antenna would not normally be expected to be a transmitting antenna because of its poor efficiency, dispersion and match. The observation is that the match due to the additional modes excited by the single arm would improve as the number of arms increases. There are some physical limits to this approach. First as the number of arms increases the minimum radius increases for the feedpoint, thus reducing its highest frequency of operation. Secondly, getting a large number of amplifiers to track amplitude and phase over frequency and temperature maybe quite costly.

The phenomenon shown in Figure 5.2 is the result of probing the MAW spiral with 50Ω inputs at each arm to ground. Unlike the Deschamps formula, these impedances inherently are relative to ground

and thus produce a slightly different result than the full mode impedance with all arms excited. The important characteristic shown in this figure is that if all arms are directly input into coax instead of through a balun, the average impedance actually decreases with arm count. These geometries do have a short linear tapered section to reduce the overall impedance at higher frequencies. The reactive component of these designs is small until the switch from equiangular to modulated near the feed point to prevent etching problems, which adds an inductive term that becomes about 25% of the impedance at $20 f_0$.

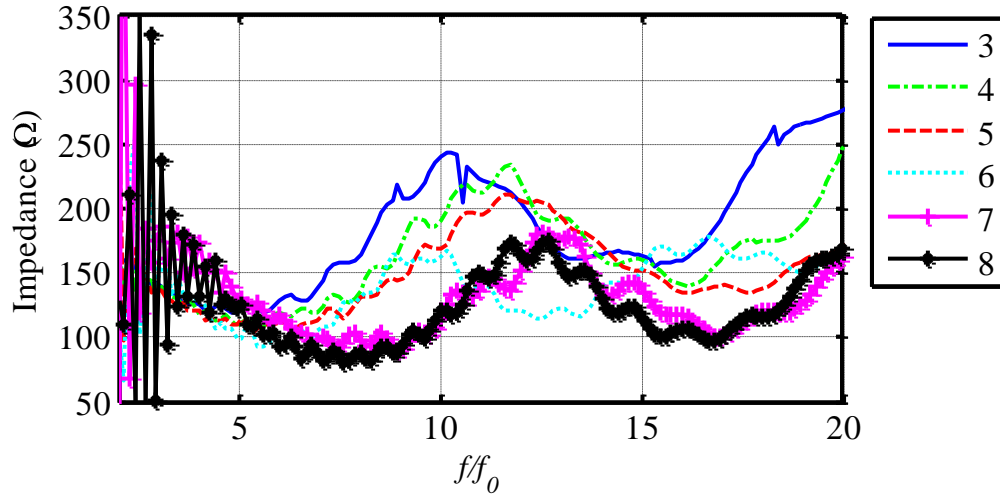


Figure 5.2 Impedance of a single arm for various arm counts.

5.1.2 Patterns of Multi-Arm MAW Spirals

The important characteristic of the multi-arm geometry is whether it can control the radiation patterns of the element. There are two categories of control, the first being met by the Butler matrix beamformer, that all power incident on the multi-port geometry be converted. Other than the mismatch term the spiral utilizing the Butler matrix or equivalent device can sort the detected voltages into a unique and orthogonal detection port. Any imperfections in the beamformer represent potential received power that is reradiated away. The second category that is of more practical application for distinguishing the different arm count geometries is what power is delivered into modes that are not directly controlled. An example of this power loss would be the power in the three arm MAW spiral that is left in mode 2 even though the modulations were supposed to prevent power reaching this radiation region from the feed point. The following figures show the total amount of power controlled in the pattern versus the total

pattern radiated. This information is obtained by comparing the beamformed pattern to the ideal pattern for that mode by use of the FFT.

Odd arm count on the MAW spiral results in a very inefficient last mode, because it is effectively the reflected mode and the next mode on the other side of the bandstop is the normal spiral mode. In this condition the MAW spiral has the similar problem as the even arm sinuous, the “last” or highest mode has no control from the element or the beamformer and the antenna produces a combination of these two modes that results in 3 dB of loss from the total power available to the beamformer. Figures 5.3-5.5 show this phenomenon clearly. The three arm geometry is the most forgiving and this performance can be significantly improved by changing to a structure that is not self-complimentary. The bandstops can improve performance by slightly increasing the modulation period to move them further away from the radiation region. Note the losses from a pure mode 1 are very small, as one would expect if the antenna radiated efficiently before it can get to any higher mode regions. The chief loss mechanism for mode -1 is mode 2 for the three arm geometry.

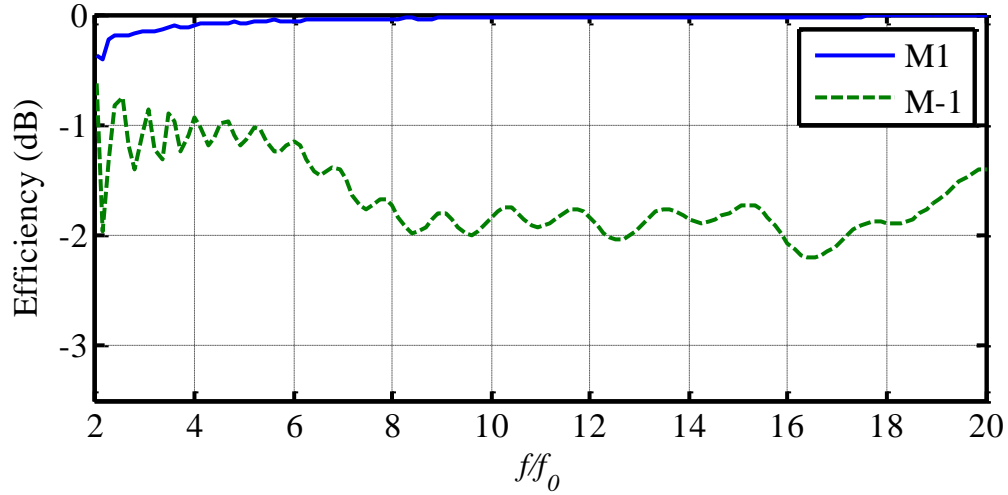


Figure 5.3: Efficiency between beamformer mode and pattern mode for a three-arm MAW spiral.

The odd arm count geometries also show an increased roll off after $(N \pm mode)f_0$ in the highest controlled mode radiating efficiently as -1, -2, and -3 for MAW spirals with arm count 3, 5, and 7, respectively. These modes are all reflected modes and as such can be contaminated by the bandstop efficiency. Returning to Figures 5.3-5 one would expect knees in the efficiencies of the modes -1, -2, and -3 at these frequencies at approximately 5, 8, and 11 or $(2N-mode)$ and there are. For the three-arm count,

there is an additional dip at 8 corresponding to $2N$, but this characteristic is less noticeable in the five and seven-arm case.

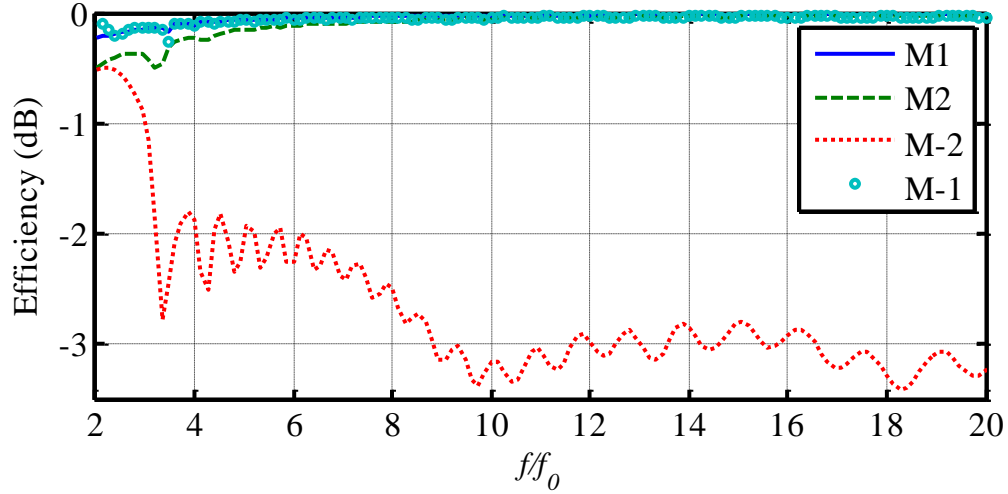


Figure 5.4: Efficiency between beamformer mode and pattern mode for a five-arm MAW spiral.

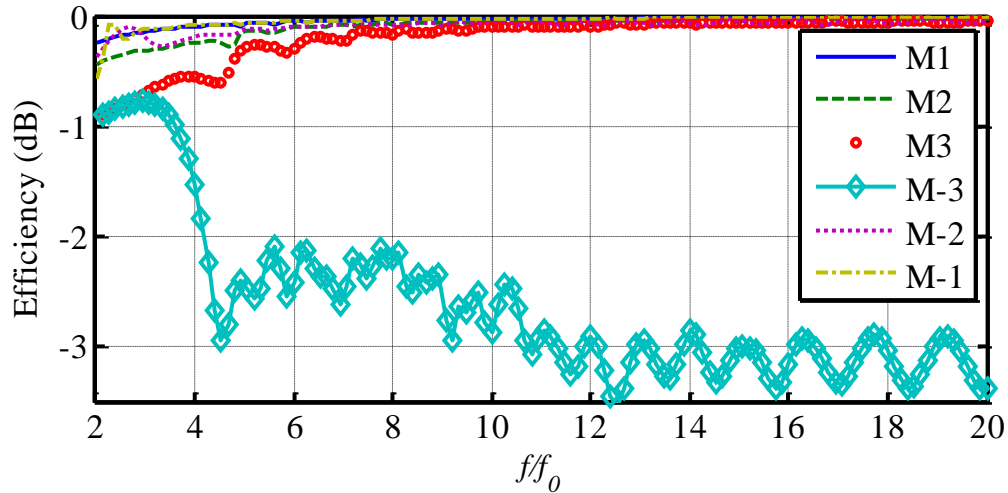


Figure 5.5: Efficiency between beamformer mode and pattern mode for a seven-arm MAW spiral.

The efficiency of all modes on the even arm count MAW spirals are better than for similar odd arm counts. This efficiency of the even count spiral is consistent with a contamination of the next mode of approximately -10 dB for even arm count as reported in Chapter 3. The contamination is lower due to the preferential polarization for the “highest” mode on the MAW spiral, which is all positive for the 4, 6, and 8 cases in Figures 5.6 – 8 and thus does not need the bandstop to be generated. Instead of multiple dB losses for the odd case, the even case only loses tenths of a dB and only in the mode that has its radiation region closest to the reverse mode with the same phasing. Otherwise the bandstops are working well.

However, the mode does not reach maximum efficiency until several times its cutoff unlike the lower modes that rise to full efficiency quickly.

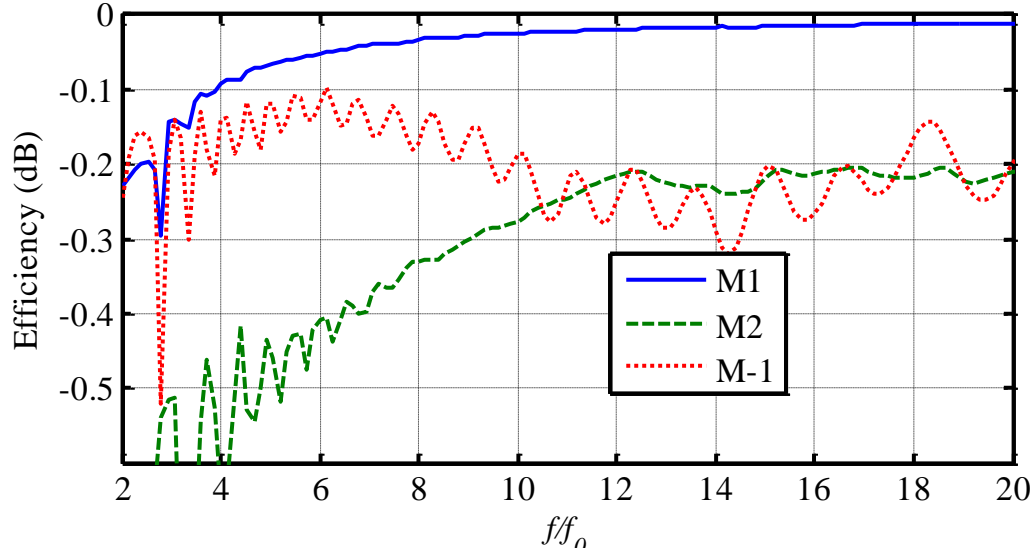


Figure 5.6: Efficiency between beamformer mode and pattern mode for a four-arm MAW spiral.

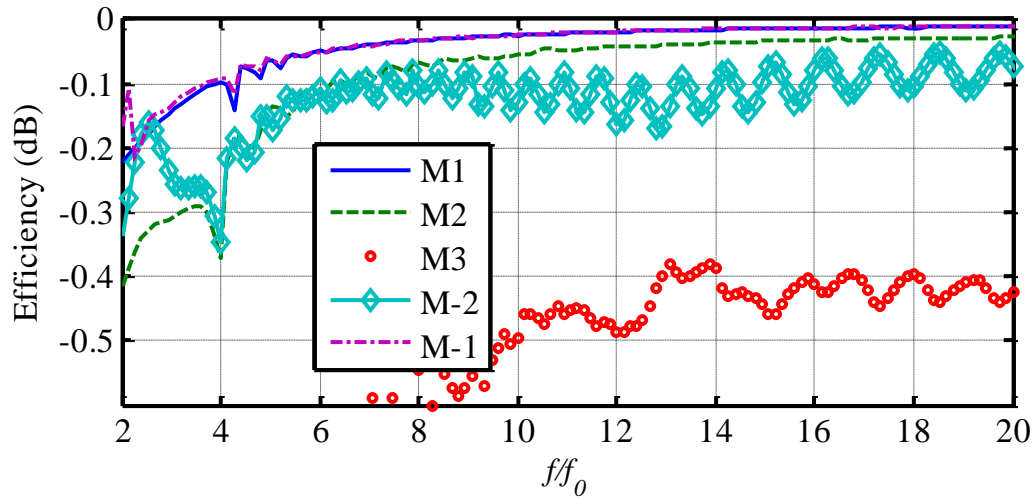


Figure 5.7: Efficiency between beamformer mode and pattern mode for a six-arm MAW spiral.

Having determined which modes are likely to be useful for providing beams of low modal contamination for the element designs, we next investigated AoA performance of several of the highly efficient modes using the four-arm mode 1 and 2 self-complementary as our lower limit for useable AoA performance. Part of the reason for comparing efficiency was that the larger the loss to other modes, the poorer the expected accuracy of the antenna element. Figure 5.4 shows much higher efficiency meaning less contamination for mode 2. To arrive at a way to display the improvement in AoA from a four to a

five arm spiral, a figure of merit must be developed. First, to understand better the antenna, the pattern needs to be represented in two dimensions to show the pattern structure. Then the two patterns should be compared on the basis of uncertainty between the two modes for an arbitrary incident field.

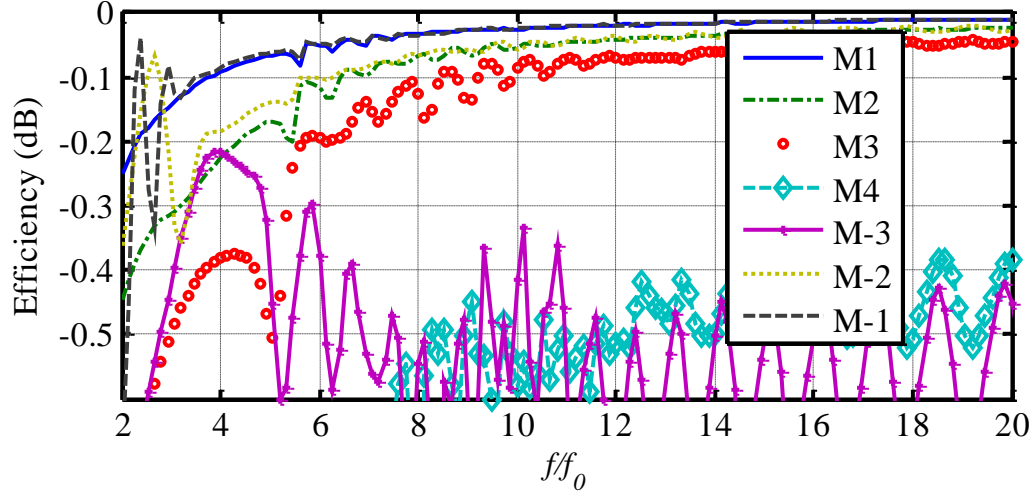


Figure 5.8: Efficiency between beamformer mode and pattern mode for an eight-arm MAW spiral.

5.1.3 Simulated AoA

Figure 5.9 shows the pattern of a mode 2 four-arm MAW spiral at $10 f_0$. The two contours show the response respectively to a RCP and LCP signal. The pattern peaks at about 38° and has a very symmetric shape for the RCP response. However, it only poorly rejects the LCP signal at about -10 dB. This LCP response is effectively the error vector for the AoA performance of the antenna.

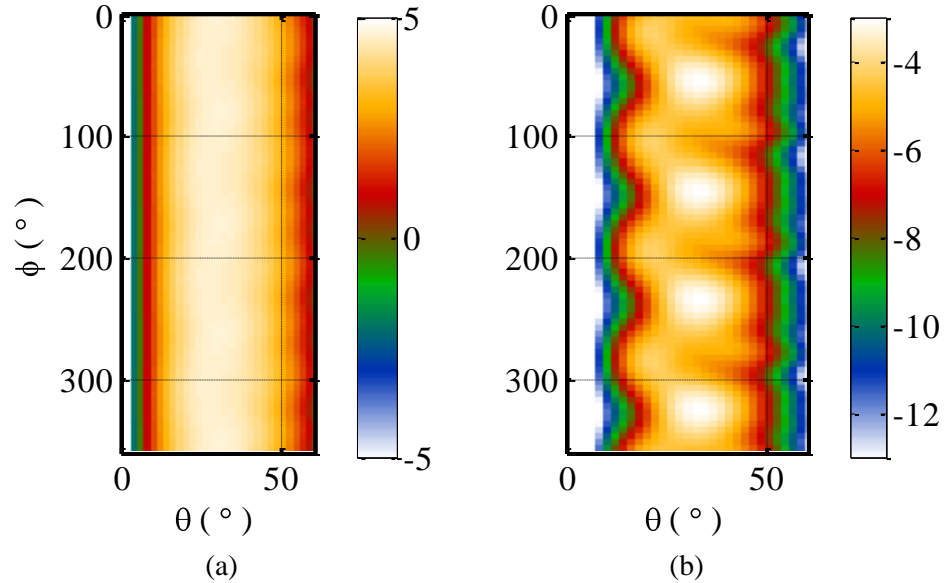


Figure 5.9: Four-arm self-complementary MAW spiral pattern, mode 2; (a) RCP, (b) LCP.

The same response for the five-arm geometry shows a tremendous reduction in this orthogonal component in Figure 5.10 where the error vector is improved almost 15 dB. This corresponds to the reduced uncertainty of the angle this sensor can determine from $\pm 17^\circ$ in ϕ to $\pm 3.2^\circ$, a large improvement as shown in Figure 5.11. Obviously implementing the five-arm solution with conventional hybrids would be difficult but the 10 dB improvement in accuracy might justify the approach. Alternately, using six arms would provide the best of both polarimetry and AoA, with a more practically realizable beamformer. The six-arm MAW spiral would provide two independent very accurate measurements of both AoA and polarization for a received signal while only adding one channel to the four-arm MAW design.

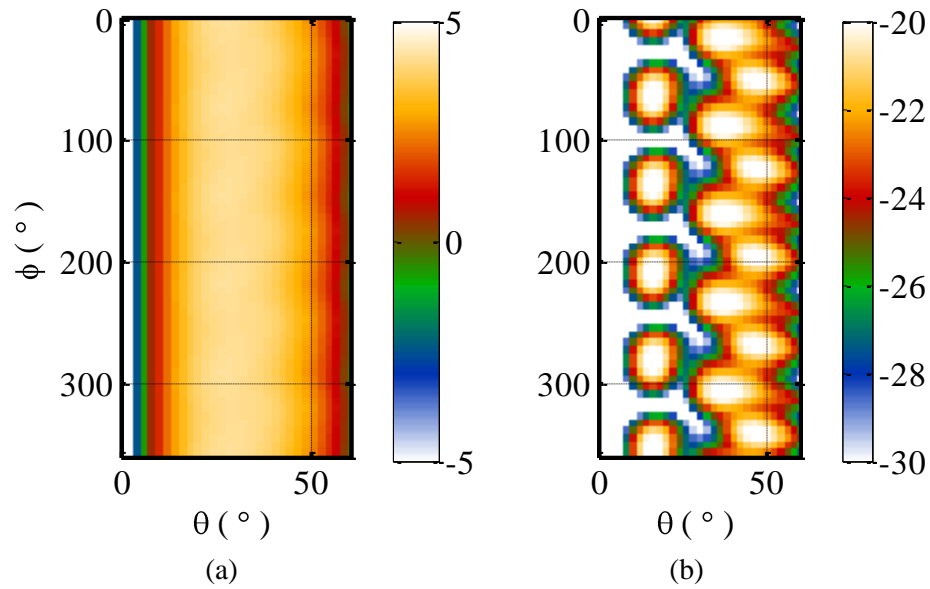


Figure 5.10: Five-arm self-complementary MAW spiral pattern, mode 2/mode 1 (a) RCP, (b) LCP.

Perhaps the best way to describe the mode residue shown in Figure 5.11 is as the error on locating a linear emitter. Because the antenna is circularly polarized, this residue should represent the worst error for approximately 50% of the Poincare sphere relative to matched polarization. In this case, the four-arm AoA capability is shown as 40%, whereas the five-arm using the same information is 8% or 5 times the accuracy for one more arm. Review of the six-arm geometry showed only very modest improvement over the five-arm case for the single polarization AoA, but the reverse polarization AoA response was much better (10 dB) than the four-arm AoA single polarization difference mode response. The implication is that the performance of a six-arm MAW spiral should be excellent for normal monopulse AoA designs. A significant performance sacrifice arises for lower arm counts, and because the six-arm geometry should

provide three different AoA responses 2/1, -2/-1, and 3/2 to confirm the angular detection it will be more accurate. Only the last ratio 3/2 is significantly degraded, except if the emitter is cross-polarized to the mode of the antenna.

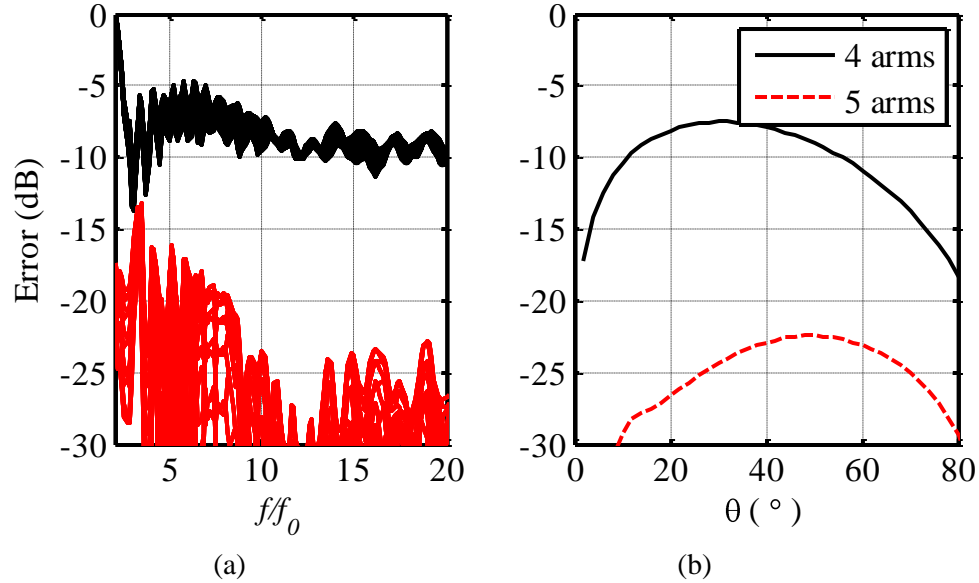


Figure 5.11: Four-arm compared to 5 arm Self-Complementary MAW spiral AoA statistics, mode 2/mode 1. The figure on the left shows the spread over frequency at $\theta = 30^\circ$ for the error vector, the figure on the right shows the average error over all frequencies and ϕ (linear weighting) versus θ .

5.2 Archimedean Comparison

Shown in Figure 5.12 is the comparison between the broadside gains in forward and reverse modes for three different embodiments of the equiangular and Archimedean MAW spirals. As seen, the Archimedean eight-arm has higher gain than the corresponding four-arm MAW spiral. However, the eight-arm would probably lose a similar amount of power due to matching the much higher impedance exceeding 250Ω . The plots do not include the losses due to mismatch, which into the nominal 50Ω balun would be over 1 dB. The anomaly at $f/f_0=2$ in the equiangular reverse mode is a resonance problem in the first design chosen; based on the study of four-arm spirals the element can easily be tuned to mitigate this behavior. The particular designs chosen for this initial check had a high expansion factor due to the high number of arms, specifically, 2.5 for the equiangular and 4 turns on the Archimedean. The result of the rapidly increasing structure can be seen with the broadside response only having one cycle across an 8:1 bandwidth, but with a much larger fluctuation in gain than most of the designs investigated in chapter 2.

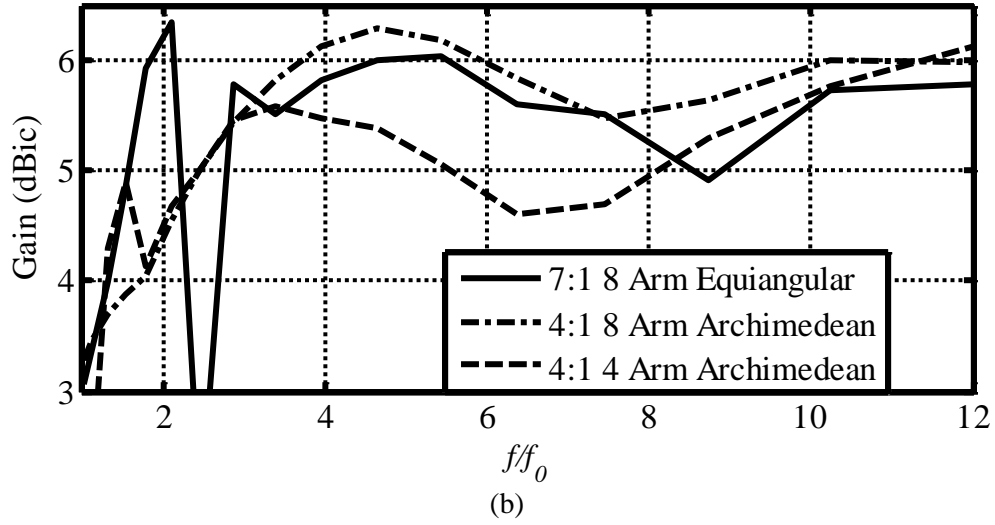
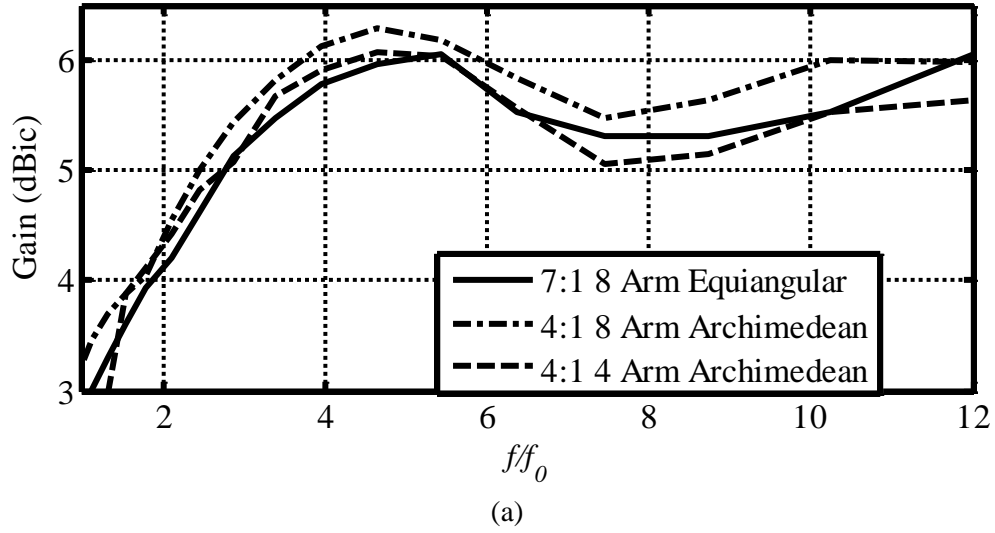


Figure 5.12: Broadside gains for four- and eight-arm MAW spirals in (a) forward and (b) reverse modes of operation.

While WoW was not shown here, the number would have been too low to verify, 0.02 dB at $10 f_0$ for both geometries at 30° and still below 0.45 dB at 60° . This mathematical result will not be approached by a fabricated design but at least shows the improvement of having the ability to separate a single mode for the nearest seven modes versus only the three available in the four-arm design. The suppression of the pattern asymmetry would make this antenna much more desirable if it were not for the complex beamformer regardless of the element geometry. Similar behavior is not as easily achieved with the sinuous because of the high coupling between arms resulting in the same type of response explained in Figure 5.12 (b) where the antenna will have a very narrow anti-resonance similar to the characteristics of conventional log periodic antennas.

The best cross-polarization performance of the reverse mode for a four-arm antenna is about 10 dB worse than that of an eight-arm MAW irrespective of the geometry or modulation greater than 3. This improvement is due to the suppression of mode 3 for reverse operation, since now the term will be absorbed in the beamformer rather than delivered to the port for mode -1. Finally, the effects of the growth type (Archimedean vs. equiangular) on the pattern and impedance of an eight-arm MAW spiral are shown in Figure 5.13 and 5.14, respectively. As seen, results were slightly better for the Archimedean for all parameters except wide angle cross-polarization, which is still over 20 dB down with only a 4:1 modulation.

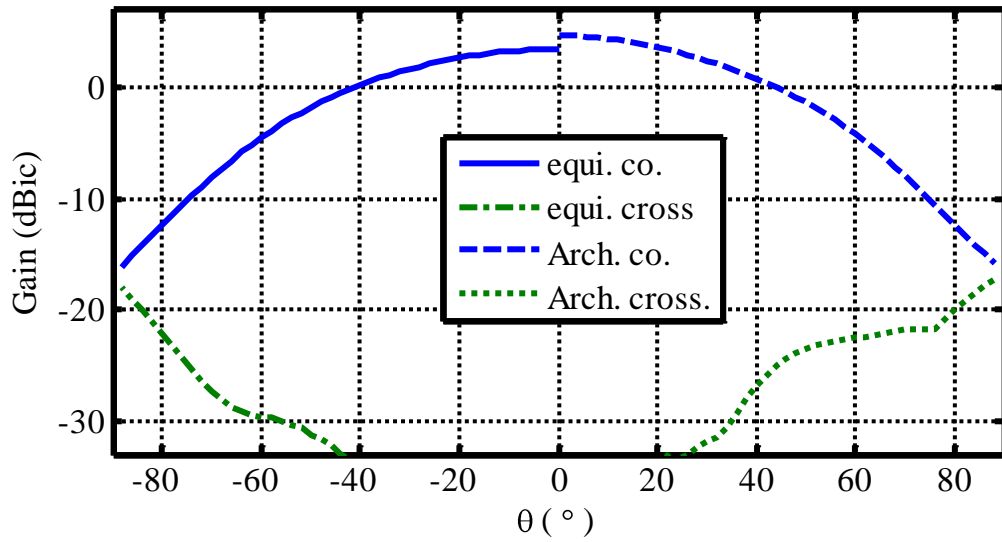


Figure 5.13: Comparison of equiangular and Archimedean eight-arm MAW spirals average patterns.

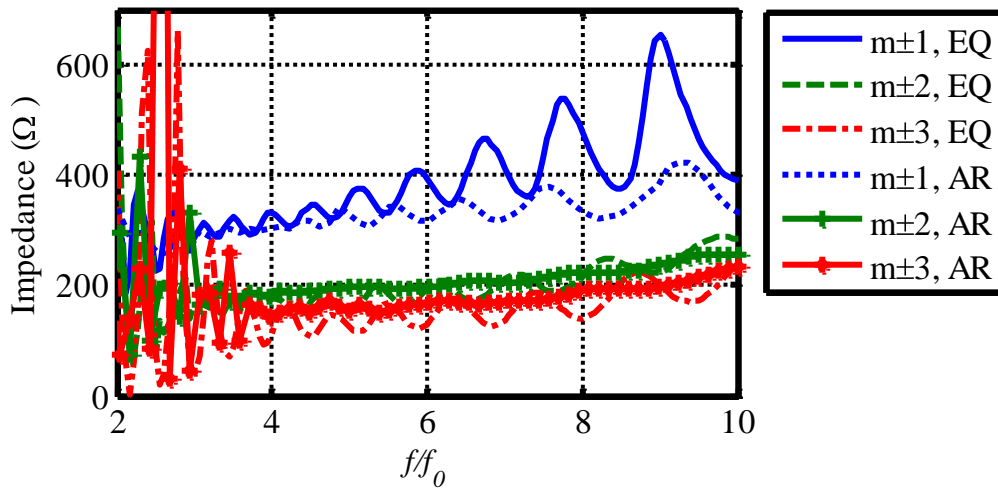


Figure 5.14: Comparison of equiangular and Archimedean eight-arm MAW spirals impedance.

It is important to note that the greater number of arms, although significantly improving the far-

field properties of the MAW spiral, also increases the complexity of the beamforming network. Assuming that additional modes are needed (example: monopulse direction finding); an eight-arm MAW will enable the simultaneous excitation of modes 1, 2, 3, -1, -2, and -3. Certainly, the overlapping mode bandwidth will be reduced with the addition of these higher order modes. Additionally, the impedance matching will also represent a significant loss to the mode not optimized.

5.3 Phase-Center Variation

The phase center variation of the MAW spiral regardless of arm count remains less than a tenth of a wavelength across the frequency band at 60° . This angle (120° full beamwidth) is approximately where the antenna would be used to provide a 10 dB aperture taper in mode 1 as a reflector prime focus feed. Modes 2 and 3 would have different angles for optimal efficiency due to the null, but if the antenna were to be used as a feed, the maximum aperture efficiency should be on the sum mode. Shown phase error in Fig. 5.15 for using the element face as the reference plane results in less than 0.02 dB in aperture efficiency loss for a typical reflector for the 60° beamwidth ($F/D = 0.3$). Figure 5.15 shows the scale in wavelengths at the frequency plotted rather than absolute distance; obviously positional accuracy of the phase center increases linearly with frequency above $2f_0$.

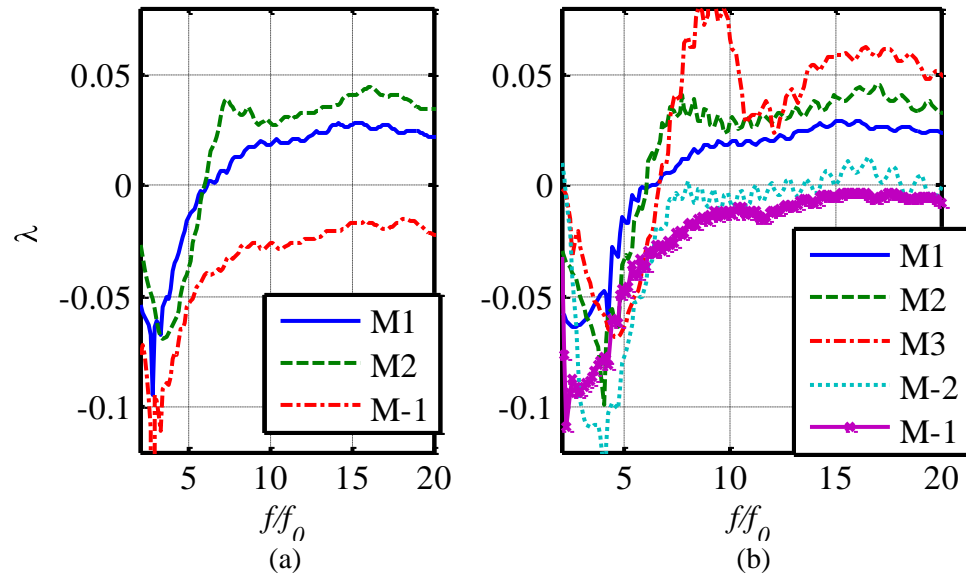


Figure 5.15: Four-arm compared to six-arm self-complementary MAW spiral phase center statistics, all modes, (a) shows four-arm MAW spiral, (b) shows six-arm MAW spiral.

The phase center for the difference modes was taken slightly off broadside at 18° due to the null

not being a good phase reference. Figure 5.15 only shows the average response, but the important result for reflectors is the average displacement along the z-axis. The higher arm count MAW spirals have the same bias as the four-arm where the reflected modes image just slightly below the xy plane and the forward modes are slightly above due the twist in the pattern at wide angles.

CHAPTER 6

CONCLUSION

6.1 Summary of Work and Contributions

Multi-polarized spiral antennas are separated into two categories based on bandwidth. Specifically, for many applications, the best design uses multiple feeding methods to achieve bandwidth up to several octaves. While this research briefly investigated introduction of ports outside the center of the geometry, the area of interest quickly focused on truly frequency independent geometries. The MAW spiral is the only spiral antenna able to provide this capability. In the investigation beyond the decision to concentrate on FI geometries, the antenna design was frequently compared to the more commonly used (sinuous and spiral) geometries for any preferential capability.

The performance of the MAW spiral was shown to be similar to a sinuous antenna for dual polarized performance as long as the geometry was highly dispersive. For less dispersive geometries the MAW spiral distributes its performance degradation more heavily on reverse operation including loss, cross-polarization and pattern symmetry than the sinuous, which typically has identical performance in both modes. For single polarization performance the equiangular spiral will outperform both geometries on polarization, impedance flatness, and pattern symmetry, which is why it is often used in AoA.

The MAW spiral was characterized relative to its design parameters including modulation ratio, modulation period, growth rate, arm count, termination, cavity and dielectric effects. Usefulness of various geometries was defined against performance parameters including polarization, impedance, pattern symmetry and angle of arrival. It is seen that in order for a four-arm MAW spiral to compete in

performance with other FI designs it needs an expansion rate of less than 1.5 and modulation ratio greater than 4. One slight drawback to the MAW spiral is that the opposite polarizations have a difference in response time due to the method used to generate reverse polarized patterns with bandstop reflections, while the sinuous have the same delay for both polarizations.

The four-arm MAW spiral does provide a limited AoA capability that is much better than that available on the four-arm sinuous antenna although easily outperformed in single polarization for four-arm geometries by any single polarization spiral. With modern AoA systems that use frequency detection and pattern lookup tables, the MAW spiral can provide more information than the equiangular spiral because it provides a unique triple voltage response for three well behaved spiral modes that are inherently orthogonal functionally. The spiral cannot provide polarization information because it only receives one polarization and the sinuous will only provide polarization information and will need a second antenna (or more) to do interferometry or AoA.

Several alternate geometries of the MAW spiral were investigated including Archimedean, average metal to gap areas not equal to one, periods of the MAW spiral that were not self-complimentary, element thickness, termination lengths, feed point launch tapers, and arm counts. The following findings were made:

- Archimedean MAW spiral antennas outperform equiangular spiral antennas at frequencies close to cutoff because of the additional turns being distributed to the maximum radius.
- Increasing the overall ratio of metal to slot improves the match if the nominal input impedance is 50Ω for both Archimedean and equiangular spirals. The expected improvement will recover much of the 1 dB mismatch loss without changing antenna patterns, although the resistive losses will increase.
- If the period of the bandstops for the MAW spiral are less than that of a self-complimentary case, the polarization performance of the modes radiating inside the bandstop ring improves, but the gain flatness is degraded.

- If the period of the bandstops for the MAW spiral is greater than the self-complementary case, the polarization may improve slightly, but is limited by the ability of the bandstop to prevent radiation in the next mode (3 in the case of the four-arm MAW spiral).
- Increasing the element thickness, while not typically practical, will lower the modal impedance of the spiral by very large amounts consistent with the transmission line model.
- Termination of the MAW spiral works best with an open in a low impedance section, eliminating most of the anti-resonance at double the f_0 of the MAW spiral.
- A taper at the feed point can be used to lower impedance of the MAW spiral but has limited effectiveness due to the upper frequency limit of the bandstops interacting with the taper causing the inductive term of the structure to increase.
- MAW spirals with N arms have N-1 useable modes, N-2 of which are very free of modal contamination with reasonable design parameters. The “last” mode works much better on the even number arm antennas with a typical cross-polarization term of -10 dB due to the element wrap. For the odd number arm antennas this mode is highly contaminated by the forward mode making it almost linearly polarized.
- Three arm MAW spirals can generate two well behaved orthogonal sum modes, unfortunately the second mode has modal contamination at -6 dB, which can only be mitigated by about 3 dB using a different modulation period. This response is still better than any other odd arm case.
- Pattern modal content is reduced in mathematical synthesis by 10 dB by the addition of one arm to the four-arm MAW spiral reducing the initial uncertainty from 30% to less than 3% for a positional prediction.
- Input impedance of the single arm MAW spiral is only moderately affected by the arm count, this property allows potential application with arms directly exciting amplifiers before having the modes beamformed in a later section of the receiver.

For practical designs, the MAW spiral requires cavities with absorber for optimum performance [76]. The investigation showed that the amount of energy reflected from the cavity for conventional materials was not significantly higher than for a perfect matched layer treatment. The cavity had negligible effect on the pattern without the absorber. The dielectric has a fairly large effect on the performance of the MAW spiral, especially on the designs that are not self-complementary.

6.2 Future Work

The future investigation of MAW spiral should center on the following areas: improving bandstop performance so less bandstops are needed to get more efficient reflected modes and reduce the contamination from modes outside the bandstop region. The current bandstop could possibly have increased effectiveness if the overall average impedance was lower by making the element thicker and thus shifting the lower impedance down significantly. Simulations have shown that even with fairly thin metal the impedance on the planar element can be lowered to 50Ω from 110Ω or even lower making the relative range of impedances larger. However, getting all the reflection to occur in one bandstop will be difficult without degrading the wideband impedance.

Improving the absorber design to reduce cavity depth would be another area to improve this design. If a ferrite is used, depending on the frequency minimum the material thickness could be reduced and complimented with a carbon based material for frequencies above which the magnetic material will typically cease to have absorptive properties. Other recent research has recommended that the more computationally efficient method for modeling this type of cavity will be FDTD possibly using the commercial application CST [77] due to the frequency variable material properties.

Other areas of interest involve investigating the trades for the MAW spiral as a lens feed and improving the hybrids from the component used in this research with one that had much less loss. Also of some interest, especially since it was part of the initial patent is better understanding of the conical MAW spiral configuration. In particular, how well does it behave when the reverse mode of operation is now separated radially and angularly, how consistent are the two modes for effective phase center, and does the period need to be changed to compensate for the angle of the cone. Developing circuits to compensate

for the modal dispersion would also make the antenna more attractive, but was outside the scope of the current research. If the circuit could be developed to compensate the dispersion of the modes, it should be straightforward to change its parameters to mimic the geometric phase growth of each mode.

BIBLIOGRAPHY

- [1] J. D. Dyson, "The Equiangular Spiral Antenna," *IRE Transactions on Antennas and Propagation*, Vol. 7, Issue 2, pp 181-187, April 1959
- [2] J. A. Kaiser, "The Archimedean Two-Wire Spiral Antenna," *IRE Transactions on Antennas and Propagation*, Vol. 8 Issue 3, pp 312-323, May 1960
- [3] R. H. Duhamel, "Dual Polarized Sinuous Antenna, U.S. Patent 703042, Feb. 1985.
- [4] V. K. Tripp, "The Microstrip Sinuous Antenna", *Antennas and Propagation Society Symposium*, 1991, *AP-S Digest*, 52-55, June 1991
- [5] D. E. Isbell, "Log Periodic Dipole Arrays", *IRE Transactions on Antennas and Propagation*, Vol. 8 Issue 3, pp 260-267, May 1960
- [6] K.M.P. Aghdam, "Compact dual-polarisation planar log-periodic antennas with integrated feed circuit". *Microwaves, Antennas and Propagation, IEEE Proceedings-* Vol. 152 Issue 5, pp 359-366, 2005
- [7] P. G. Ingerson; "Modulated Arm Width Spiral Antenna," U. S. Patent 3,681,772, Aug. 1, 1972
- [8] Duhamel, R.H., and Isbell, D.E.: 'Broadband logarithmically periodic structures'. pp 119–128, *IRE International Convention Record*, Mar. 1957.
- [9] V. H. Runsey, "Frequency Independent Antennas", *IRE International Convention Record*, Vol. 5, pp 114-119, Mar. 1957.
- [10] H. G. Booker, "Slot Aerials and Their Relation to Complementary Wire Aerials (Babinet's Principle)", *Journal of the IEE – Part IIIA: Radiolocation*, Vol. 93, Issue 4, 620-625, 1946
- [11] I. Tzanidis, "Low Profile Spiral on a Thin Ferrite Ground Plane for 220-550 MHz Operation," *IEEE Transactions on Antennas and Propagation*, Vol. 58, No 11, pp 3715-3720, Nov. 2010
- [12] D. L. Smith, "The Trap-Loaded Cylindrical Antenna," *IEEE Transactions on Antennas and Propagations*, Vol. 23, Issue 1, pp 20-27, Jan. 1975

- [13] P. Ingerson, "Log-Periodic Antennas with Modulated Impedance Feeders," *IEEE Transactions on Antennas and Propagation*, Vol. 16, Issue 6, pp 633-642, Nov. 1968.
- [14] Pozar, D., *Microwave Engineering*, 2nd Edition, J. Wiley, pg. 449-450, 1998
- [15] M. J. Colbourn, "Graph Isomorphism and Self-Complementary Graphs," *SIGACT News*, pp 25-29, Spring 1978.
- [16] G. E. Deschamps, "Impedance properties of Complementary Multiterminal Planar Structures," *IRE Transactions on Antennas and Propagations*, Vol 7, Issue 5, pp 371-379, Dec. 1959.
- [17] . P. G. Ingerson; "Comparison of Sinuous and MAW Spiral Antennas for Wideband, Dual Polarized Multi-Arm Applications," *Proceedings of the Antenna Applications Symposium*, Vol. 2 Sept 1991
- [18] "Advanced Technology Apertures", *Cobham Sensor Systems*,
<http://www.cobham.com/media/101034/APERTURES.pdf> (Accessed 4/15/2011)
- [19] "Dual Polarized Sinuous Technology", *L3 Communications*, <http://www.l3com.com/randtron/dcpantenna.htm> (Accessed 4/15/2011)
- [20] "2-18 GHz Dual Polarised Sinuous Antennas", *Q-Par Angus Ltd.*, <http://www.q-par.com/products/sinuous-antennas/2-18-ghz-dual-polarized-sinuous-antennas> (Accessed 4/15/2011)
- [21] G. Andrews; "Broadband Center Fed Spiral Antenna," U. S. Patent 4,243,993, Jan. 6, 1981.
- [22] G. Andrews; "Broadband Spiral Antenna with Tapered Armwidth Modulation," U. S. Patent 4,605,934, Aug. 12, 1986.
- [23] R. M. Honda, "Constant Beamwidth Spiral Antenna", U. S. Patent 4,725,848, Feb. 16, 1988.
- [24] C. Walter; "Multi-mode Dual Circularly Polarized Spiral Antenna," U. S. Patent 5,451,973, Sept. 19, 1995.
- [25] J. D. Taylor, *Introduction to Ultra Wideband Radar Systems*, CRC, 1995.
- [26] "FCC notice of proposed rulemaking, revision of part 15 of the commission's rules regarding ultra-wideband transmission systems," *Federal Communications Commission*, Washington, DC part 15 of ET-Docket 98-153.

- [27] M. Nikoufard, "An 8×25 GHz polarization independent integrated multi-wavelength receiver," *Technical Digest Integr. Photon. Res. (IPR '04)*, p. IThB2, San Francisco, USA, Jun. 30–Jul. 2 2004
- [28] T. Milligan, *Modern Antenna Design*, John Wiley & Sons, p. 541, 2005
- [29] D. S. Filipovic, T. P. Cencich, Frequency Independent Antennas, *Ch. 13 in 4th Edition of Antenna Engineering Handbook*, pp.13.1-13.67, McGraw Hill, 2007.
- [30] Ingerson, F.G., "The Modulated Arm Width (MAW) Spiral Antenna ," *Abstracts of the 20th Annual Symposium USAF Antenna Research and Development Program*, Oct 13, 14, 15, 1970.
- [31] E. Caswell, "Design and Analysis of Star Spiral Antenna with Application to Wideband Arrays with Variable Element Sizes," *Dissertation Virginia Polytechnic Institute and State University*, p. 97, 2001
- [32] D. Tammen, "Numerical Studies of the Sinuous Spiral Antenna," *1993 Antennas and Propagation Society International Symposium*, pp 446-449 Vol.1, 1993
- [33] T. Hertel, "On the dispersive properties of the conical spiral antenna and its use for pulsed radiation," *IEEE Transactions on Antennas and Propagations*, Vol. 51, Issue 7, p. 1426-1433, July 2003
- [34] E. K. Miller, "Short-pulse characteristics of the conical spiral antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 25, Issue 5, pp. 621-626, May 1977
- [35] R. Anders, "Phase velocity on a conical two-armed logarithmic foil-type spiral antenna," *IEEE Transaction on Antennas and Propagations*, Vol. 17, pp 233-234, 1969.
- [36] S. Yang, "Research on Pulse Radiation of Planar Equiangular Spiral Antennas," *Fourth Advanced International Conference on Telecommunications*, pp. 36-42, June 2008.
- [37] W. N. Kefauver, T. P. Cencich Sr., D. S. Filipovic, "Effects of Modulation Ratio on the Performance of 4 Arm MAW Spirals," *31st Antenna Applications Symposium*, 2007, pp 328-346.
- [38] Eric Weinstein, "Logarithmic Spiral", *Wolfram Mathworld*,
<http://mathworld.wolfram.com/LogarithmicSpiral.html> (accessed 4/15/2011)

- [39] T. MacNamara, "Simplified Design Procedure for Butler Matrices Incorporating 90° and 180° Hybrids," *IEE Proc. H, Microwave and Antenna and Propagation*, 1987, pp. 50–54.
- [40] T. Cencich; "Simultaneous mode matching feedline," U. S. Patent 6,549,175, April 15 2003.
- [41] J. Mruk, "Band Rejection Methods for Planar Log Periodic Antennas," *IEEE Transactions on Antennas and Propagation*, Vol. 58, Issue 7, pp 2288-2294, July 2010
- [42] O. Klemp, "On the MIMO Capacity of Planar, Log.-Per. 4-Arm Antennas," *European Conference on Wireless Technology*, pp 121-124, Oct.2005
- [43] FEKO User's Manual Suite 6.0, *EM Software & Systems-S.A. (Pty) Ltd*, 2010.
- [44] High Frequency Structure Simulation (HFSS), v.12, *Ansoft LLC.*, Pittsburgh, PA, Nov. 2010.
- [45] R. Bawer, "The Spiral Antenna," *IRE International Convention Record*, p84-91, Mar. 1960
- [46] S. Kuo, "Multiple Polarization Spiral Antenna," U. S. Patent 3,562,756, Feb. 9, 1971.
- [47] C. P. Wen, "Attenuation characteristics of coplanar waveguides," *Proceedings of the IEEE*, pp. 141-142, Jan. 1970
- [48] J. A. Huffman and T. P. Cencich, "Modal Impedances of Planar, Non-Complementary, N-fold Symmetric Antenna Structures," *IEEE Antennas and Propagation Magazine*, Vol. 47, No. 1, pp 110-116, Feb. 2005.
- [49] R. Elliot, "Pulse Waveform Degradation Due to Dispersion in Waveguide", *IRE Transactions on Microwave Theory and Techniques*, Vol. 5, Issue 4, pp. 254-257, Oct. 1957
- [50] A. Taflove and M.E. Brodwin, Numerical Solution of Steady-State Electromagnetic Scattering Problems Using the Time-Dependent Maxwell's Equations, *IEEE Microwave Theory and Techniques*, Vol. MTT-23, No. 8, pp. 623-630, August 1975.
- [51] W. Kefauver, T. Cencich, D. Filipovic, "Modulated Arm Width (MAW) Spiral: Theory, Modeling, Design and Measurements". *IEEE Transactions on Antennas and Propagation*, Vol. 58 Issue 11, pp. 3515-3523, Nov. 2010.
- [52] J. P. Berenger, "A perfectly matched layer for the absorption of electromagnetic waves", *Journal. Computational. Physics.*, vol. 114, pp. 185-200, Oct. 1994.

- [53] J. Dyson, "A note on the Difference Between Equiangular and Archimedes Spiral Antennas," *IRE Transactions on Microwave Theory and Techniques*, Vol. 9, Issue 2, pp 203-205, 1961
- [54] N. Stutzke, "Broadband two-arm dual-mode dual polarized spiral antenna," *2005 IEEE International Antennas and Propagation Symposium, Volume. 1B*, pp 414-417, July 2005
- [55] D. S. Filipovic, T. P. Cencich, Sr.; "Frequency Independent Antennas," *Antenna Engineering Handbook, Fourth Edition, Chapter 13*, McGraw Hill, 2007.
- [56] R. Harrington, *Time Harmonic Electromagnetic Fields*, McGraw Hill, 1961
- [57] J. Dyson, P. Mayes, "New Circularly-Polarized Frequency-Independent Antennas with Conical Beam or Omnidirectional Patterns," *IRE Transactions on Antennas and Propagation*, p. 334-342, July, 1961
- [58] N. Marchand, "Transmission-Line Conversion Transformers," *Electronics*, Vol. 17, pp. 142-146, Dec. 1944
- [59] G. D. Kent, "A Resonant Mode Dielectrometer for Substrates," *37th ARFTG Conference Digest – Spring*, pp 21-24, 1991
- [60] J. Carr, "Broad-Band Radio Frequency Interferometer," *IRE Transactions on Instrumentation*, Volume I-8, Issue 2, pp. 39-43, 1959
- [61] F. Adcock, "Improvements in Means for Determining the Direction of a Distant Source of Electromagnetic Radiation," Great Britain Patent, 1919
- [62] S. E. Lipsky, *Microwave Passive Microwave Direction Finding*, SciTech Publishing, Inc., 2004..
- [63] R. G. Corzine and J. A. Mosko, *Four Arm Spiral Antennas*, Norwood, MA, Artech House, 1990
- [64] J. Kaiser, "Phase Comparison Properties of the Dual Mode Spiral with Application to Direction Finding," *1964 International Antennas and Propagation Symposium*, pp 67-72, 1964.
- [65] M. Wheeler; "Passive Direction Finder System," U. S. Patent 3013,265, December. 12,1961.
- [66] S. McMillan; "Log Spiral Design for Direction of Arrival Estimation," *1991 International Antennas and Propagation Symposium*, Volume 2, pp. 719-722, Jun, 1991

- [67] G. Kemp, "Ultra-wideband Quadrature Coupler," *Electronic Letters, Volume 19, Is. 6*, pp. 197-200, March, 1983
- [68] G. Lank, "Exact Angular Accuracy of an Amplitude Comparison Sequential-Lobing Processor," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 10, Issue 3, pp 393-397, May 1974
- [69] D. Goldstein, *GPS Wing, Air Force Global Positioning Systems Wing*, "Request for Feedback on GPS IIR-20 (SVN-49) Mitigation Options",
http://www.navcen.uscg.gov/pdf/gps/news/Mar2010_svn49/GPSW_SVN_49_inf_Brief_Mar_2010_Final.pdf (accessed 4/15/2011)
- [70] L. Bullock, "Precision Broadband Direction-Finding Techniques," *1967 International Antennas and Propagation Symposium, Volume 5*, pp. 224-232, July 1967.
- [71] W. Nester, "The fast Fourier transform and the Butler matrix," *IEEE Transactions on Antennas and Propagation, Vol. 16, Issue 3*, pp. 360, May 1968.
- [72] FEKO, "Modeling of Dielectric Materials in FEKO", *FEKO Quarterly*, March 2005
http://www.feko.info/about-us/quarterly/FEKO_Quarterly_Mar_2005.pdf (accessed 4/15/2011)
- [73] Eccosorb LS, *Emerson & Cumming Technical Literature*, May 2007.
- [74] W. Kefauver, T. Cencich, D. Filipovic, "Four-Arm Modulated Arm Width Spiral Antennas for Simultaneous Omni-Polarized RF Emitter Sensing and Determination of the Angle of Arrival," *Proceedings of 32nd ESA Antenna Workshop on Antennas for Space Applications*, Noordwijk, Netherlands, Oct. 2010.
- [75] G. Deschamps, "The Logarithmic Spiral in a Single-Aperture Multimode Antenna System," *IEEE Transaction on Antennas and Propagations, Volume 19, Issue 1*, pp 90-96, Jan, 1971
- [76] M. Buck, "Spiral Cavity Backing Effects on Pattern Symmetry and Modal Contamination," *IEEE Antennas and Wireless Propagation Letters, Vol.5, Issue 1*, pp 243-247, 2006.
- [77] M. Kolrdintserva, "Extraction of Lorentzian and Debye Parameters of Dielectric and Magnetic Dispersive Materials For FDTD Modeling," *Journal of Electrical Engineering, Vol 53, No, 9*, pp 97 – 100, 2002.